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ABSTRACT

This module applies basic laws of thermodynamics to the study of the efficiency at which heat can be converted to other useful forms of energy, including heat at low temperatures. The module is divided into four major sections. Section I treats energy conversion efficiency and defines the concept of first-law efficiency, the most widely used indicator of efficient energy use. Past, present, and future trends in first-law efficiency for a variety of energy conversion devices are presented. Section II introduces the concept of available work and defines second-law efficiency (which is based on the available work concept). Second-law efficiency provides another, possibly superior, means of determining the potential for reduction in energy use due to improvement in energy conversion processes. Several examples of second-law efficiency are worked out for single source/single output devices. In addition, second-law efficiency is determined for a variety of tasks. In section III several energy conversion systems are analyzed from the standpoint of both first-/second-law efficiency. Section IV provides Fortran computer programs which apply concepts developed in the module to the analysis of combined energy systems and their potential for reduced fuel. Bibliography, an audio-visual materials list, and a list of prerequisite mathematics/physics skills needed are included. (JN)

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THERMODYNAMIC EFFICIENCY

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An Issue Oriented Module

Prepared for

American Association of Physics Teachers

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PREREQUISITE MATHEMATICS SKILLS AND PHYSICS CONCEPTS

a. MATHEMATICAL AND COMPUTATIONAL COMPETENCIES

i. College-level algebra
ii. Graph reading
iii. Fortran language

b. PHYSICS COMPETENCIES

i. Energy
ii. Heat
iii. Internal Energy
iv. Work
v. Temperature
vi. Temperature scales - Fahrenheit, Celsius, Kelvin
vii. Thermodynamic cycle
viii. Pressure, volume, temperature relationships ($pV=nRT$) for the ideal gas
ix. Adiabatic process (pV^{γ} = constant)
x. Heat reservoir
xi. First law of thermodynamics - Conservation of energy
xii. Second law of thermodynamics
xiii. Entropy
xiv. Carnot's Theorem
xv. Heat of combustion
xvi. Fuel
xvii. Carnot engine
xviii. Carnot refrigerator
xix. Carnot efficiency
xx. Reversible process
xxi. Irreversible process

The overall level of treatment in this module is comparable to that of an undergraduate level course in heat and thermodynamics. Calculus is not used in this module.

". . . for most activities in the residential and commercial sector of the U. S. economy, second-law efficiencies are less than 0.10, clear indications that energy is being used inefficiently today."

It is possible to conclude: "that the 1973 living standard of the U.S. could have been provided with about 40% less energy."

(see page 61)

TABLE OF CONTENTS

0. INTRODUCTION

PAGE NO.

a. Historical Interest in Efficient Use of Energy 1
b. The Potential for Reduced Energy Use 1
c. Module Overview 3
d. References and Footnotes 4

I. EFFICIENCY OF ENERGY CONVERSION DEVICES: Part I

a. Energy Conversion Devices 5
b. Definition of Energy Conversion Efficiency: First-Law Efficiency 7
c. Carnot Engine and Carnot Efficiency 8
d. Carnot Refrigerator and Carnot COP 10
e. Limits on First-Law Efficiency 11
f. First-Law Efficiency for Various Energy Conversion Devices 11
g. Trends in First-Law Efficiency 18
h. Limitations in Application of First-Law Efficiency 23
i. Problems 25
j. Solutions to Problems 27

II. EFFICIENCY OF ENERGY CONVERSION DEVICES: Part II

a. Definition of Efficiency: Second-Law Efficiency or Effectiveness 32
b. Available Work 33
c. Second-Law Efficiency in Terms of Available Work 35
d. Minimum Available Work for Various End Uses 36
e. Actual Available Work for Various Energy Sources 38
f. Second-Law Efficiency for Single Source - Single Output Devices 40
g. Example of Second-Law Efficiency for an Oil or Gas-fired Furnace 43
h. Example of Second-Law Efficiency for a Solar Space Heater 43
i. References and Footnotes 44

j. Problems 45
k. Solutions to Problems 46

III. ENERGY CONVERSION EFFICIENCY AND FUEL CONSERVATION

a. Efficiency of Energy Conversion Systems 49
b. System Efficiency of an Electric Power Plant 50
c. Improvement in the Efficiency of Electric Power Plants 51
d. System Efficiency for Air Conditioning and Refrigeration 52
e. System Efficiency for Electric Resistive Heating 53
f. Combined Energy Systems 54
g. Industrial Cogeneration: An Example of a Combined Energy System 58
h. Conclusion: The Potential for Fuel Conservation 60
i. References and Footnotes 64
j. Problems 66
k. Solutions to Problems 69

IV. COMPUTER ANALYSIS OF COMBINED ENERGY SYSTEMS

a. Introduction 74
b. Mathematical Model of Combined Energy Systems 74
c. Sample Computer Program 77
d. Problems for Computer Analysis 82
e. Questions 83
f. References and Footnotes 83

V. BIBLIOGRAPHY

VI. AUDIOVISUAL MATERIALS

0. INTRODUCTION

a. Historical Interest in Efficient Use of Energy

Interest in the implications of efficient use of energy dates back centuries. Benjamin Franklin invented a new fireplace which he offered for sale to the public in 1744. Franklin promoted sale of the fireplace largely on the basis of its potential for fuel savings. It is amusing to note that Franklin also mentioned the reduction in air pollution which must occur with a reduction in fuel use:

> "We leave it to the Political Arithmetician to compute, how much Money will be sav'd to a Country, by its spending two thirds less of fuel; how much Labour sav'd in Cutting and Carriage of it; how much Land may be clear'd for Cultivation; how great the Profit by the additional Quantity of Work done, in those Trades particularly that do not exercise the Body so much, but that the Work folks are obliged to run frequently to the Fire to warm themselves: and to Physicians to say, how much healthier thick built towns and Cities will be, now half suffocated with sulphury Smoke, when so much less of that Smoke shall be made, and the Air breadth'd by the Inhabitants be consequently so much purer."[1]

Much more recently, the National Energy Plan of 1977 stated that "Conservation and fuel efficiency are the cornerstone of the proposed National Energy Plan."[2]

In about 1825, the brilliant French engineer and scientist Sadi Carnot made extensive research into energy conversion processes in general and energy conversion efficiency in particular. Carnot's investigations led to the development of generalized laws (the Laws of Thermodynamics) which provide the basis for defining and measuring the efficiency of a wide variety of energy conversion processes.[3] These laws also provide the basis for determining the technological potential for reductions in energy use.

b. The Potential For Reduced Energy Use

The present-day usage of energy in the U.S. provides significant opportunities

for reduced energy use from both technological and social/economic changes. Figure (0) shows the flow of energy in the U.S. for 1973 with the waste energy clearly shown.[4] As can be seen from the figure, 65% of the energy was wasted. If the waste could be reduced to 50%, this would mean a savings of 10^{16} BTU which is equivalent to 1.7 billion barrels of oil. Even a 1% reduction in the energy wasted amounts to 0.7×10^{15} BTU, which is roughly equivalent to 110 million barrels of oil. At $20 per barrel for imported oil, this 1% reduction implies a savings of $2.2 billion for the U.S. consumer if the reduced consumption were in terms of oil. Clearly, a tremendous potential for reduced energy use exists.

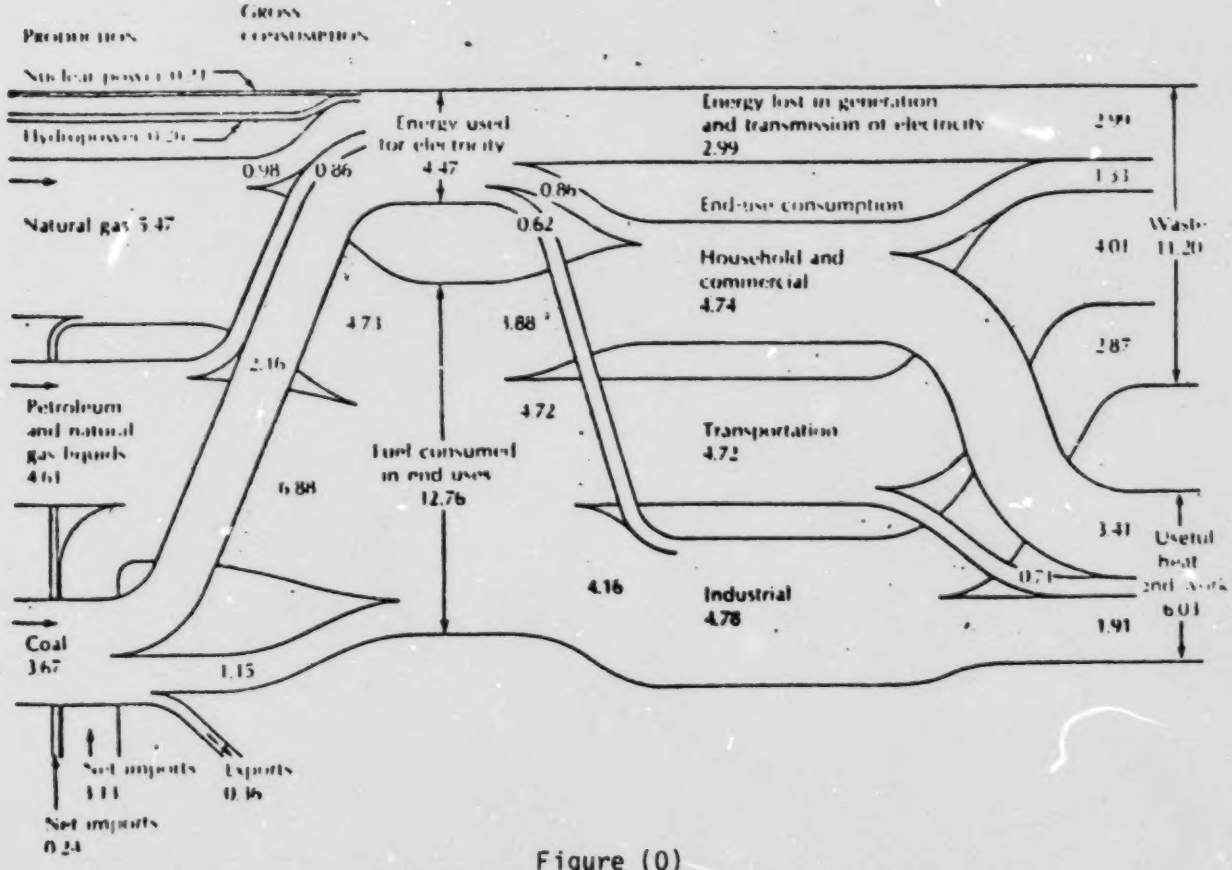


Figure (0)

Approximate flow of energy through the economy of the U.S. in 1973, exclusive of food energy. All numerical figures are to be multiplied by 10^{15} Kilocalories. The figures can be converted to BTU by multiplying by 3.968.

c. Module Overview

This module applies the basic laws of thermodynamics to the study of the efficiency at which heat can be converted to other useful forms of energy, including heat at low temperature. As seen in Figure (0), roughly 98.5% of all energy used in the U.S. in 1973 was derived from fuels in the form of heat. Actually, coal, oil, and natural gas provided 97.2% and nuclear fuel provided an additional 1.3%. Heat is by far the major form of energy which is converted to other forms for use by humans. Even solar energy will be collected mainly in the form of heat before being converted to other forms. At present, nuclear fuel provides 4% of all energy.

Section I of this module treats energy conversion efficiency and defines the concept of first-law efficiency, the most widely used indicator of efficient energy use. Past, present, and future trends in first-law efficiency for a variety of energy conversion devices are presented. Limitations in the use of first-law efficiency are outlined. Section II introduces the concept of available work. Second-law efficiency, which is based on the concept of available work, is defined. Second-law efficiency provides another, possibly superior, means of determining the potential for reduction in energy use due to improvements in energy conversion processes. Several examples of second-law efficiency are worked out for single source - single output devices. Second-law efficiency is determined for a variety of tasks. In Section III, several energy conversion systems are analyzed from the standpoint of both

first-law and second-law efficiency. The potential for reduced use is illustrated chiefly by consideration of combined energy systems for both electricity and low-temperature heat production. Section IV provides computer programs which apply the concepts developed in the module to the analysis of combined energy systems and their potential for reduced fuel use. Section V and VI include a bibliography and list of audiovisual materials, respectively.

d. References and Footnotes

1. Benjamin Franklin, An Account of the New Pennsylvania Fireplaces, 1744, as reported by E. R. Berndt, "Aggregate Energy, Efficiency, and Productivity Measurement", Annual Review of Energy, Vol. 3, 1978, pp. 225-273.
2. "The National Energy Plan - Overview and Summary", Executive Office of the President, reprinted in L. C. Ruedisili and M. W. Firebaugh, Perspectives on Energy, 2nd Ed., Oxford University Press, New York, 1978, pp. 80-94.
3. Sadi Carnot, "Reflections on the Motive Power of Heat", 1824, reprinted in W. F. Magie, The Second Law of Thermodynamics, American Book Co., available from University Microfilms, Ann Arbor, Michigan.
4. Earl Cook, Man, Energy, Society, Freeman, San Francisco, 1976, p. 313.

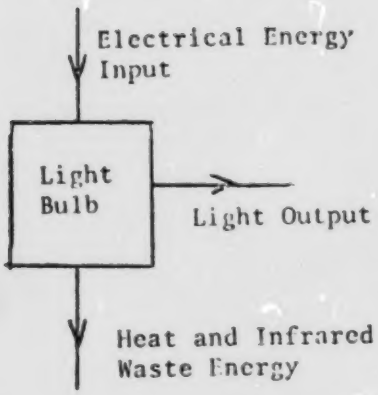
SEGMENT I. EFFICIENCY OF ENERGY CONVERSION DEVICES: Part I

a. Energy Conversion Devices

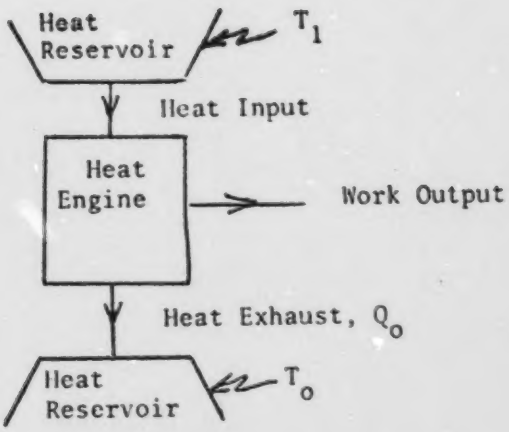
An energy conversion device is any device, mechanical or otherwise, whose purpose is to convert energy from one form into another, more useful or convenient, form. Examples of various energy conversion devices are:

* an incandescent light bulb converts the electrical energy input into light (radiant energy) as the useful energy output. There is also energy emitted as heat and infrared radiation which is usually wasted;
* a heat engine converts the heat input into mechanical energy (work) as the useful energy output. Energy is also emitted as heat exhaust which is wasted;
* a refrigerator absorbs electrical energy input and causes heat to be extracted from the cold compartment. This heat and the electrical energy input is exhausted into the surroundings of the refrigerator;
* a heat pump absorbs electrical energy input as well as heat from the cold exterior of a living space and transfers this energy into the warm living space as useful heat.

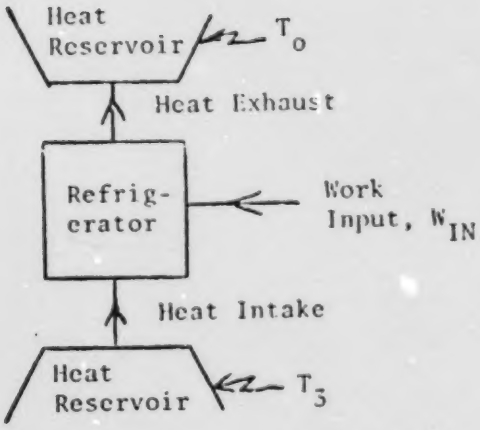
For each of these energy conversion devices there is an energy input to the device and an amount of energy of the desired kind transferred to a selected portion of the surroundings of the device. See Fig. (1)



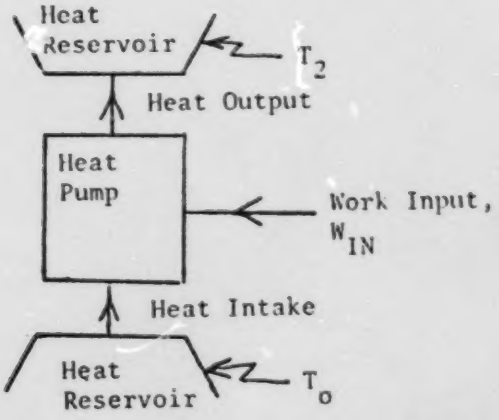
(a) Incandescent light bulb



(b) Heat engine. T_1 is the temperature of the heat source. T_o refers to the engine's surroundings.



(c) Refrigerator. T_3 refers to the cool compartment of refrigerator.



(d) Heat pump. T_2 is the temperature of the warm living space.

Figure (1)

Schematic Diagrams of Energy Conversion Devices. A heat reservoir is a system which can absorb or liberate heat with little or no change in temperature. The temperatures in the figure satisfy T_1 (hot) > T_2 (warm) > T_0 (ambient) > T_3 (cool).

b. Definition of Conversion Efficiency: First-Law Efficiency.

Each energy conversion device is designed to bring about some energy transfer between the device and a system which is part of the surroundings of the device. The energy transfer of the desired kind for which the device is designed is called the useful energy output of the device. For example, an electric motor transfers mechanical work as output; an electric generator transfers electrical energy as output; a refrigerator removes heat from its cold compartment as output; and a heat engine transfers mechanical work as output. It is usually desirable to use the least amount of energy transfer to the device possible to bring about the desired energy output. This situation arises because the energy input to the device costs money for fuel, because of equipment costs for energy collection and storage in the case of solar and wind power, or because of equipment and dam building costs in the cases of hydroelectric power.

One traditional way of determining how well an energy conversion device brings about the desired energy output is to examine a quantity η which we shall call the first-law efficiency. This quantity is defined for a given energy conversion device as,

$$\eta = \frac{\text{Energy transfer of desired kind}}{\text{Energy input}}$$

When the first-law efficiency η can be greater than 1, it is usually called a coefficient of performance (COP). Refrigerators can be described by a COP. When the maximum value of the first-law efficiency (η_{MAX}) satisfies $\eta_{MAX} < 1$, it is usually called a conversion efficiency. Heat engines can be described by a conversion efficiency. The quantity η is called first-law efficiency because it is related to the first-law of thermodynamics (conservation of energy).

c. Carnot Engine and Carnot Efficiency

A Carnot engine is an ideal energy conversion device. The Carnot engine consists of a mechanical device and some system carried through a reversible cycle by the mechanical device. The reversible cycle is called a Carnot cycle. In causing the system to be carried through the Carnot cycle, the Carnot engine transfers work to another system in its surroundings while absorbing heat. This work is the useful energy output of the engine. The Carnot cycle is shown in Fig. (2).

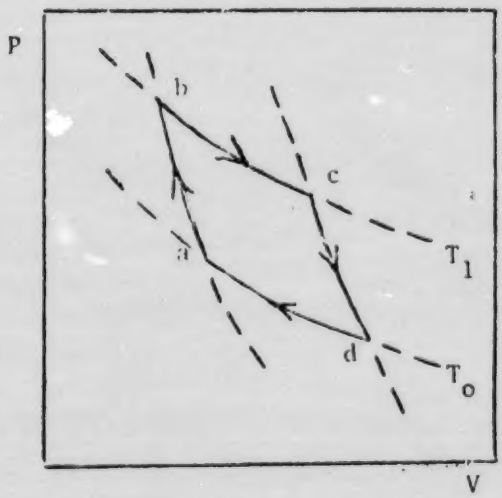


Fig. (2)

Carnot cycle. The lines ab and cd are each adiabatic processes while bc and da are each isothermal processes. The isothermal processes satisfy PV = constant while the adiabatic processes satisfy PV^γ = constant, $\gamma>1$; which means that the paths for adiabatic processes are steeper than the paths for isothermal processes. T_1 and T_0 are temperatures characteristic of the isothermal processes ($T_1 > T_0$).

During the Carnot cycle, the system absorbs heat Q_1 from a heat resevoir at

temperature T_1, the same temperature as the system during the isothermal process from b to c. The system liberates (exhausts) heat $-Q_0$ to a heat resevoir at temperature T_0. Since the system is taken through a cycle, the change in internal energy ΔU is zero, $\Delta U = 0$, according to the first law of thermodynamics. Thus, the first law of thermodynamics can be written

$$0 = (Q_1 - Q_0) - W_{OUT},$$

or

$$W_{OUT} = Q_1 - Q_0 .$$

The quantity W_{OUT} is the useful work output. The first-law efficiency for the Carnot engine is

$$\eta_{CAR} = \frac{W_{OUT}}{Q_1} = \frac{Q_1 - Q_0}{Q_1}$$

Since the Carnot cycle is reversible, the second law of thermodynamics implies the entropy change ΔS_T for the Carnot engine and surroundings is zero, $\Delta S_T = 0$. In addition, since the process is a cycle, the entropy change ΔS for the system itself is zero, $\Delta S = 0$. Thus, the second law implies that

$$\Delta S_T = \frac{Q_1}{T_1} + \frac{Q_0}{T_0} + \Delta S = 0 \text{ and } \Delta S = 0,$$

or

$$\frac{Q_0}{Q_1} = \frac{T_0}{T_1}$$

Hence, the first-law efficiency for a Carnot engine can be expressed as

$$\eta_{CAR} = 1 - \frac{T_0}{T_1}$$

which is always less than 1 as long as $T_0 \neq 0°K$ and $T_1 < \infty$.

d. Carnot Refrigerator and the Carnot COP

The ideal Carnot cycle can be operated in reverse so that the energy conversion device operates as a Carnot refrigerator. In causing the system to be carried through the Carnot cycle, the Carnot refrigerator absorbs heat Q_3 from a heat reservoir at temperature T_3 which is lower than the temperature T_0 of the atmosphere or surrounding environment. In bringing about the desired heat transfer from the heat reservoir at T_3, the Carnot refrigerator absorbs work W_{IN} and exhausts heat $-Q_0$ to the atmosphere. As in the case of the Carnot engine, the change in internal energy ΔU is zero for one cycle. Thus,

$$0 = \Delta U = (Q_3 - Q_0) + W_{IN},$$

or

$$W_{IN} = Q_0 - Q_3$$

The first-law efficiency for the Carnot refrigerator is

$$\eta_{CAR} = \frac{Q_3}{W} = \left(\frac{Q_0}{Q_3} - 1\right)^{-1}$$

The η_{CAR} for the Carnot refrigerator is a COP since its value can be greater than 1. The second law of thermodynamics implies that the total entropy change is zero, $\Delta S_T = 0$. Thus,

$$\Delta S_T = \frac{Q_3}{T_3} + \frac{Q_0}{T_0} + \Delta S = 0,$$

where the entropy change ΔS of the Carnot refrigerator is also zero, $\Delta S = 0$.

Thus,

$$\frac{Q_0}{Q_3} = \frac{T_0}{T_3} .$$

Therefore, the COP for the Carnot refrigerator is

$$\eta_{CAR} = \left(\frac{T_0}{T_3} - 1\right)^{-1}$$

e. Limits on the First-Law Efficiency

Several important limitations on the first-law efficiency arise as a result of the second law of thermodyamics. These include:

*Carnot's Theorem - All Carnot engines or refrigerators operating between the same two temperatures have the same first-law efficiency, irrespective of the nature of the system involved in the engine or refrigerator;

*No engine or refrigerator operating between two given temperatures can have a first-law efficiency larger than a Carnot engine or refrigerator operating between the same two temperatures. That is,

$$\eta < \eta_{CAR}$$

We will write the maximum first-law efficiency for any energy conversion device as η_{MAX} where obviously $\eta_{MAX} = \eta_{CAR}$.

f. First-Law Efficiency for Various Energy Conversion Devices

In this section, we will use the same notation for the various temperatures as in Fig. (1). Thus, we have the following temperature sequence--$T_1 > T_2 > T_0 > T_3$. The temperature T_1 is a hot temperature characteristic of steam at high pressure or a flame; T_2 is a warm temperature characteristic of room temperature during the winter; T_0 is

called the ambient temperature and is characteristic of the atmosphere or surrounding environment; and T_3 is a cool temperature characteristic of the interior of a refrigerator or of room temperature during the summer. The energy conversion devices which are treated as examples in this section include the following:

* electric motor
* heat engine
* electric air conditioner or refrigerator
* electric heat pump
* heat-powered heating device
* absorption refrigerator

An electric motor has an electric energy input W_{IN} and a mechanical work output W_{OUT}. The first-law efficiency is a conversion efficiency given by $\eta = W_{OUT}/W_{IN}$ and $\eta_{MAX} = 1$. A heat engine has a heat input Q_1 from a heat reservoir at T_1 and a mechanical work or electric energy output W_{OUT}. See Fig. (1). The first-law efficiency is a conversion efficiency given by

$$\eta = \frac{W_{OUT}}{Q_1}$$

A heat exhaust Q_0 occurs to the atmosphere assumed to be at ambient temperature T_0. The first law of thermodynamics implies

$$0 = (Q_1 - Q_0) - W_{OUT}$$

since the system is taken through a cycle so that the change in internal energy is zero. The last two relations yield

$$\eta = 1 - \frac{Q_0}{Q_1}$$

To determine η_{MAX}, the cycle through which the heat engine carries the system must be reversible. The total entropy change ΔS_T can be written

$$\Delta S_T = \frac{Q_1}{T_1} + \frac{Q_0}{T_0} + \Delta S$$

where ΔS is the entropy change of the system and the other terms (of the form Q/T) are the entropy changes of the heat reservoirs. Since the process is a cycle and is reversible, $\Delta S = 0$ and $\Delta S_T = 0$, respectively. This means

$$-\frac{Q_1}{T_1} + \frac{Q_0}{T_0} = 0,$$

or

$$\frac{Q_0}{Q_1} = \frac{T_0}{T_1},$$

for the reversible cycle. Thus,

$$\eta_{MAX} = 1 - \frac{T_0}{T_1} \quad \text{(Heat engine)}$$

Of course $\eta_{MAX} = \eta_{CAR}$.

An electric air conditioner or refrigerator has an electric energy input W_{IN} and removes heat Q_3 from the cool compartment at the temperature T_3. See Fig. (1). An amount of heat $(-Q_0)$ is exhausted to the surrounding environment at T_0. The first-law efficiency is a COP given by

$$\eta = \frac{Q_3}{W_{IN}}$$

The first law of thermodynamics implies

$$W_{IN} = Q_0 - Q_3$$

since the change in internal energy is zero for a cycle. To obtain the value of η_{MAX}, the system must be taken through a reversible cycle so that the total entropy change and entropy change of the system both vanish. Then, the entropy changes of the heat reservoirs must add up to zero as in the case of the heat engine. So,

$$-\frac{Q_3}{T_3} + \frac{Q_0}{T_0} = 0.$$

The last three relations can be combined to give

$$\eta_{MAX} = \left(\frac{T_0}{T_3} - 1\right)^{-1} \quad \text{[Electric refrigerator or air conditioner]}$$

An electric heat pump has an electric energy input W_{IN} and transfers heat $(-Q_2)$ into a warm living space at the temperature T_2. See Fig. (1). It also absorbs heat Q_0 from the atmosphere at ambient temperature T_0. The first-law efficiency is a COP given by

$$\eta = \frac{Q_2}{W_{IN}}$$

The first law of thermodynamics implies

$$W_{IN} = Q_2 - Q_0$$

since the change in internal energy is zero as before. To obtain η_{MAX}, the cycle must be reversible. Then, the entropy changes of the heat reservoirs must add up to zero. Thus,

$$-\frac{Q_2}{T_2} + \frac{Q_0}{T_0} = 0.$$

The last three relations can be combined to give

$$\eta_{MAX} = \left(1 - \frac{T_0}{T_2}\right)^{-1} \qquad \text{(electric heat pump)}$$

A heat-powered heating device has a heat input Q_1 which is absorbed from a hot reservoir at T_1. See Fig. (3). A useful amount of heat $(-Q_2)$ is transferred to a living space at the warm temperature T_2. It also exhausts waste heat $(-Q_0)$ to the atmosphere at ambient temperature T_0. The first-law efficiency is a COP given by

$$\eta = \frac{Q_2}{Q_1}$$

The first law implies

$$0 = Q_2 - Q_1 + Q_0$$

since $\Delta U = W = 0$. To obtain η_{MAX}, the cycle must be reversible. Then, the entropy changes of the heat reservoirs must add up to zero as before. Thus,

$$-\frac{Q_1}{T_1} + \frac{Q_2}{T_2} + \frac{Q_0}{T_0} = 0.$$

the last three relations can be combined to give

$$\eta_{MAX} = \frac{\left(1 - \frac{T_0}{T_1}\right)}{\left(1 - \frac{T_0}{T_2}\right)} \qquad \text{(Heat-powered heating device)}$$

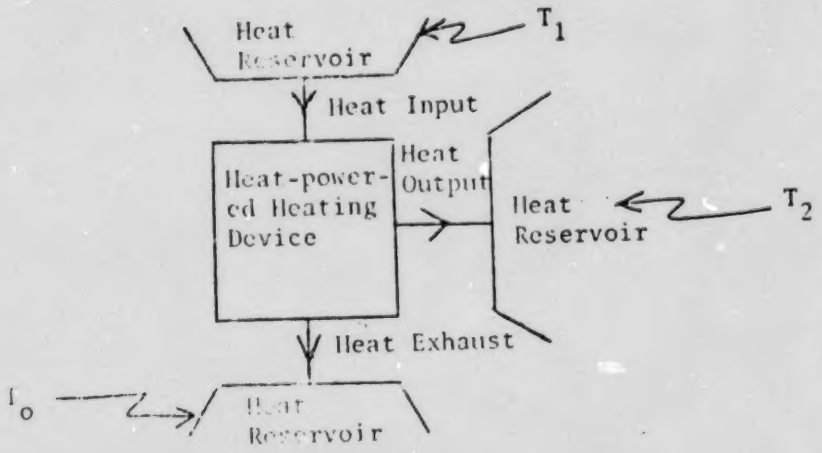


Fig. (3)

Heat-powered heating device.

Note: A furnace is a special case where the process is not a thermodynamic cycle. There η is a conversion efficiency and $\eta_{MAX} = 1$.

The absorption refrigerator has a heat input Q_1 to the device at temperature T_1. See Fig. (4). This causes an amount of heat Q_3 to be absorbed from the cold compartment of the refrigerator at temperature T_3. The heat Q_3 is the useful energy transfer. There is an amount of heat $(-Q_0)$ exhausted to the atmosphere at ambient temperature T_0. The first-law efficiency is a COP given by

$$\eta = \frac{Q_3}{Q_1}$$

The first law implies

$$0 = Q_1 + Q_3 - Q_0,$$

since $\Delta U = W = 0$. To obtain η_{MAX}, the cycle must be reversible. Then, the

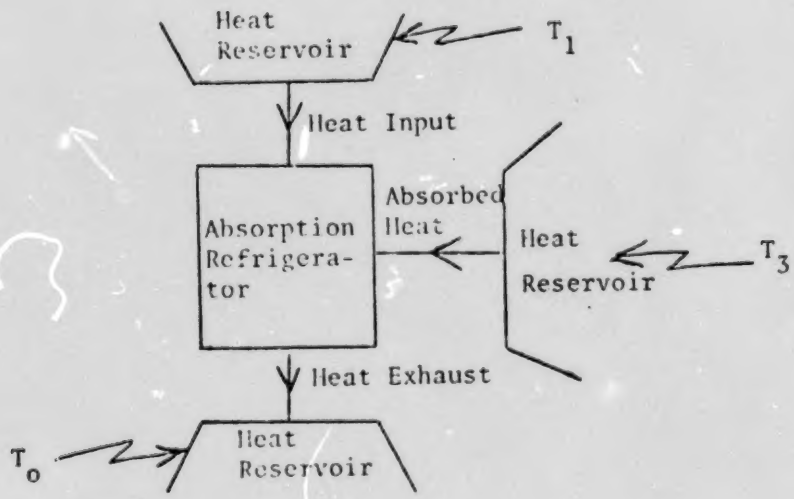


Fig. (4)

Absorption refrigerator

entropy changes of the heat reservoirs must add up to zero as before. Thus,

$$-\frac{Q_1}{T_1} - \frac{Q_3}{T_3} + \frac{Q_0}{T_0} = 0.$$

The last three relations can be combined to give

$$\eta_{MAX} = \frac{1 - \frac{T_0}{T_1}}{\frac{T_0}{T_3} - 1} \quad \text{(absorption refrigerator)}$$

Table (1) summarizes the results of this section.

g. Trends in First-Law Efficiency

The energy conversion devices in use in our society cover a broad range in first-law efficiencies. Table (2) lists many devices which are described by a conversion efficiency (with the maximum value of 1.0). The conversion efficiencies range from 0.04 for an incandescent lamp to 0.99 for an electric generator. As shown in Fig. (0) in the Introduction, the average conversion efficiency in the U.S.A. in 1973 was 35%. A major reason for this low average conversion efficiency is due to the fact that the heat engines presently in use have conversion efficiencies less than 0.50. Since approximately 99% of U.S.A. energy is provided by heat from fuels, the heat engines are a major limitation on the efficiency of conversion of the heat from fuels into other more useful forms of energy.

Heat engines (and refrigerators) have undergone major improvements in conversion efficiency in the past. See Fig. (5). Another way to examine the trends in conversion efficiency is to look at the average conversion efficiency of devices according to type of energy output. See Fig. (6). Both Figs. (5) and (6) show rather dramatic increases in conversion efficiency in the past, occuring mainly since 1900. For example, the conversion efficiency of the steam turbine of the type used in coal-fired electric power stations has increased from about 0.05 in 1900 to 0.47 at present. The impact of this increase in conversion efficiency cannot be underestimated. For example, the total amount of coal produced in the U.S.A. in 1974 was 600 million tons of which 400 million tons was used to generate electricity. Assuming that the

Type of device or system [a]	Numerator in ratio defining η	Denominator in ratio defining η	η_{MAX}	Standard nomenclature
Electric motor (W/W)	Mechanical work output	Electric work input	1	Efficiency
Heat pump electric (Q/W)	Heat Q_2 added to warm reservoir at T_2	Electric work input	$\frac{1}{1-(T_0/T_2)} > 1$	Coefficient performance (COP)
Air conditioner or refrigerator, electric (Q/W)	Heat Q_3 removed from cool reservoir at T_3	Electric work input	$\frac{1}{(T_0/T_3)-1}$ (not restricted in value)	COP
Heat engine (W/Q)	Mechanical or electric work output	Heat Q_1 from hot reservoir at T_1	$1 - \frac{T_0}{T_1} < 1$	Efficiency (thermal efficiency)
Heat-powered heating device [b] (Q/Q)	Heat Q_2 added to warm reservoir at T_2	Heat Q_1 from hot reservoir at T_1	$\frac{1-(T_0/T_1)}{(T_0/T_2)} > 1$	COP or Efficiency
Absorption refrigerator [c] (Q/Q)	Heat Q_3 removed from cool reservoir at T_3	Heat Q_1 from hot reservoir at T_1	$\frac{1-(T_0/T_1)}{(T_0/T_3)-1}$ (not restricted in value)	COP

a. The symbols W and Q refer to work and heat, respectively.

b. A furnace is a special case; for it, $\eta_{MAX}=1$. More generally, the device could include heat engine and heat pump; then $\eta_{MAX}>1$

c. "Absorption refrigerator" means any heat-powered device for cooling.

Table (1) First-law efficiency. $T_1 > T_2 > T_0 > T_3$ (Source: "Efficient Use of Energy, A Physics Perspective", ed. by W. Carnahan et. al., in Efficient Energy Use, American Institute of Physics, New York 1975).

Device	Conversion Efficiency ($\eta_{MAX} = 1$)	Energy Transformation Input - Output
Electric generator	0.99	Mechanical - electrical
Large electric motor	0.92	Electrical - mechanical
Dry cell	0.90	Chemical - electrical
Large steam boiler	0.88	Chemical - thermal
Home gas furnace	0.85	Chemical - thermal
Wet cell	0.72	Chemical - electrical
Home oil furnace	0.65	Chemical - thermal
Small electric motor	0.62	Electrical - mechanical
Fuel cell	0.60	Chemical - electrical
Liquid fuel rocket*	0.58	Chemical - thermal - mechanical
Steam turbine*	0.47	Thermal - mechanical
Gas laser	0.39	Electrical -radiant
Diesel engine*	0.38	Chemical - thermal -mechanical
Aircraft gas turbine*	0.35	Chemical - thermal - mechanical
Industrial gas turbine*	0.33	Chemical - thermal - mechanical
High intensity lamp	0.32	Electrical - radiant
Solid state laser	0.30	Electrical - radiant
Automobile engine*	0.25	Chemical - thermal - mechanical
Flourescent lamp	0.20	Electrical - radiant
Wankel engine*	0.18	Chemical -thermal - mechanical
Solar cell	0.10	Radiant - electrical
Steam locomotive*	0.08	Chemical -thermal - mechanical
Incandescent lamp	0.04	Electrical - radiant

Table (2): Efficiency of Energy Conversion Devices (Source: C. Summers, "The Conversion of Energy", Sci. Amer., Vol. 224, Sept. 1971, p. 148.) The asterisk signifies a heat engine.

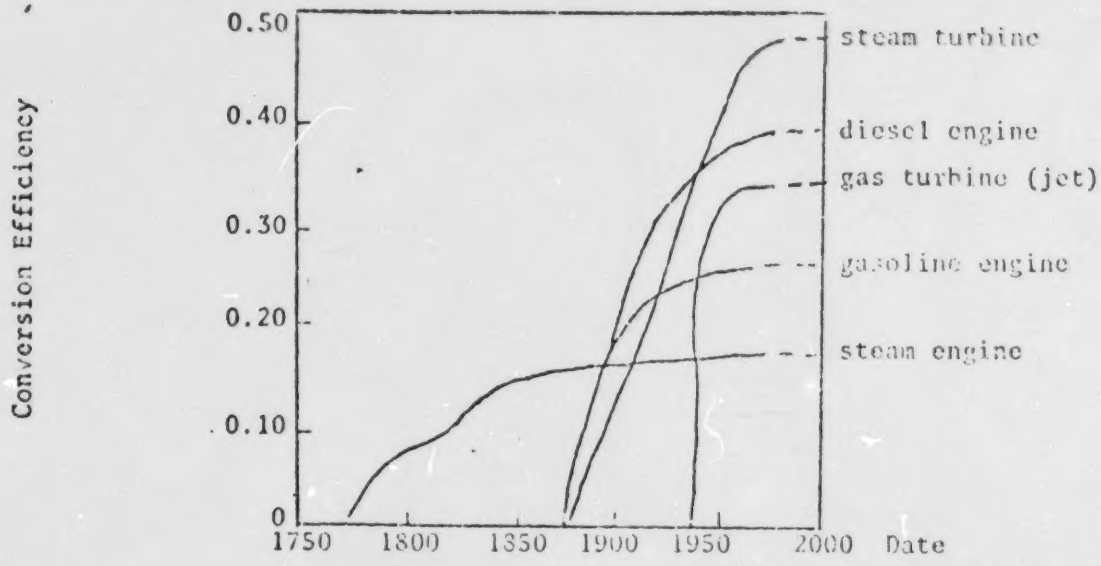


Fig. (5)

Conversion efficiency of various heat engines. The dotted lines represent entrapolations to 2000. (Source: R.S. Rouse and R.O. Smith, Energy-Resource, Slave, Pollutant, Macmillan, 1975).

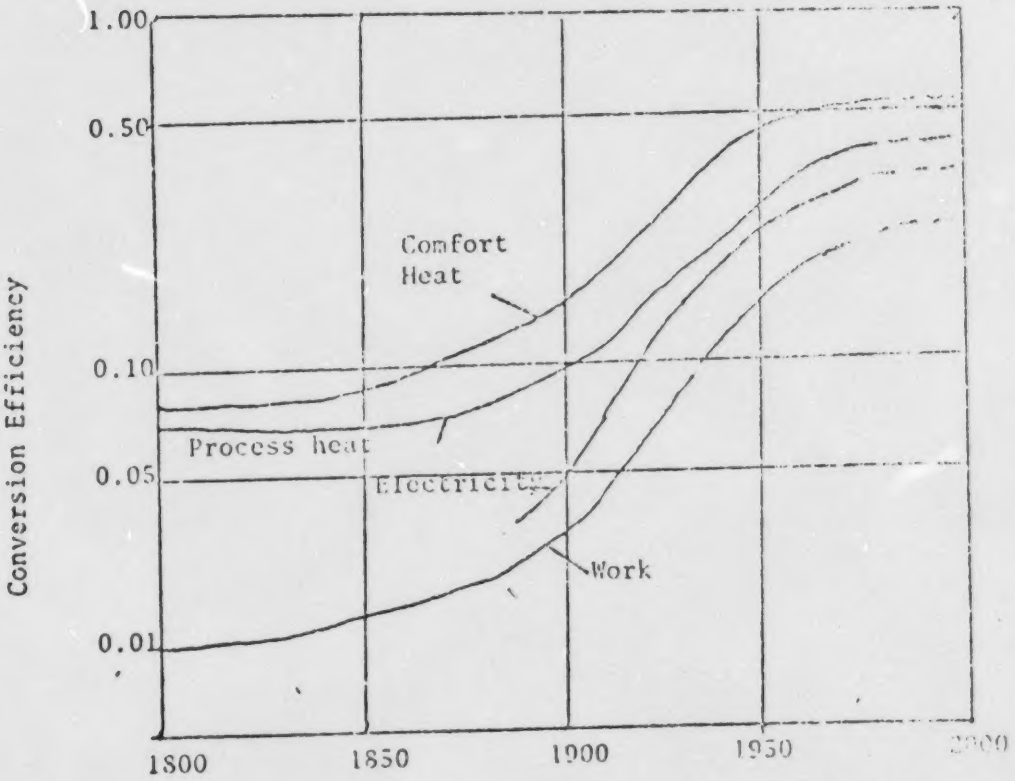


Fig. (6)

Conversion efficiencies by type of useful energy output. The dotted lines are projections to 2000. (Source: Chauncey Starr, "Energy and Power", Sci. Amer. Vol. 224, p. 40 (Sept. 1971)

average conversion efficiency of the steam turbines was about 0.35 in 1974, this would mean that 7 times as much coal, or 2800 million tons, would have been required to generate the same amount of electricity if the conversion efficiency was 0.05. Thus, total coal production would have had to be 5 times greater in 1974.

It can also be seen in Figs. (5) and (6) that the projections to the year 2000 show a definite decrease in the rate of increase in conversion efficiencies. The main variable affecting conversion efficiency is the temperature difference between which the device operates. That is, increasing the high temperature T_1 or decreasing the ambient temperature T_0 improves the conversion efficiency. Ambient temperature is very difficult to lower, although steam turbines do so by creating a slight vacuum on the low temperature end of the turbine. In this ways the steam can be used down to about $40^{o}C$. Obviously, there is a limit to the low temperature attainable. Increases in the high temperature T_1 seem an attractive way for increasing conversion efficiency. However, there are many practical problems in increasing T_1. For example, a metal like copper melts at about $1077^{o}C$. (In fact, a temperature of $1000^{o}C$. is sometimes referred to as the metallurgical limit on T_1). The highest temperature steam turbines already operate at T_1 = $600^{o}C$. Moreover, as T_1 is increased, the change in conversion efficiency decreases. To see this, consider the Carnot efficiency for several temperature T_1 with T_0 = 300°K. See Fig. (7). This figure shows significant improvement in the Carnot efficiency for changes in T_1

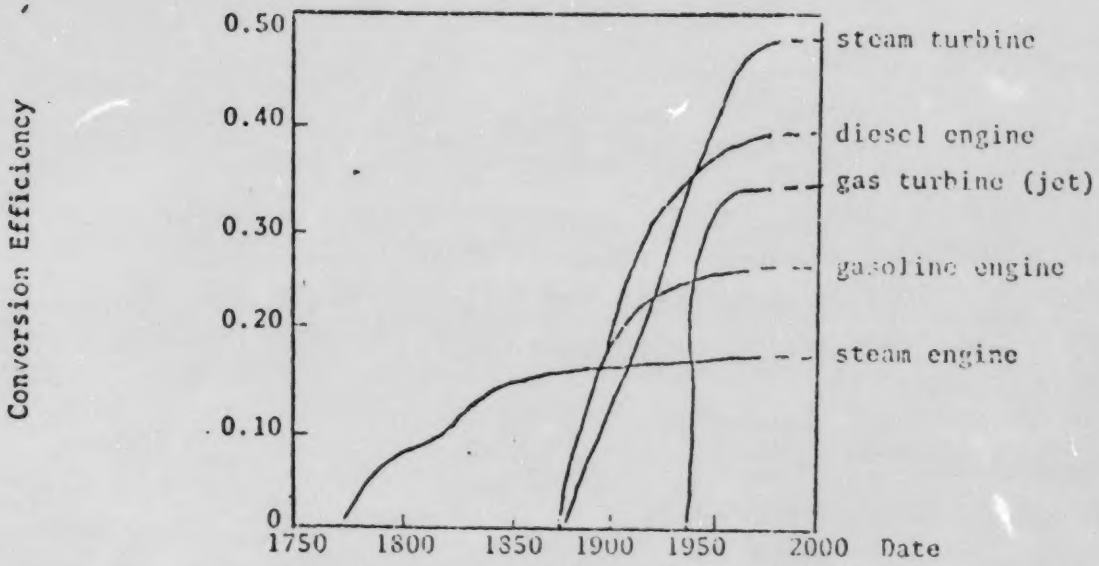


Fig. (5) Conversion efficiency of various heat engines. The dotted lines represent entrapolations to 2000. (Source: R.S. Rouse and R.O. Smith, Energy-Resource, Slave, Pollutant, Macmillan, 1975).

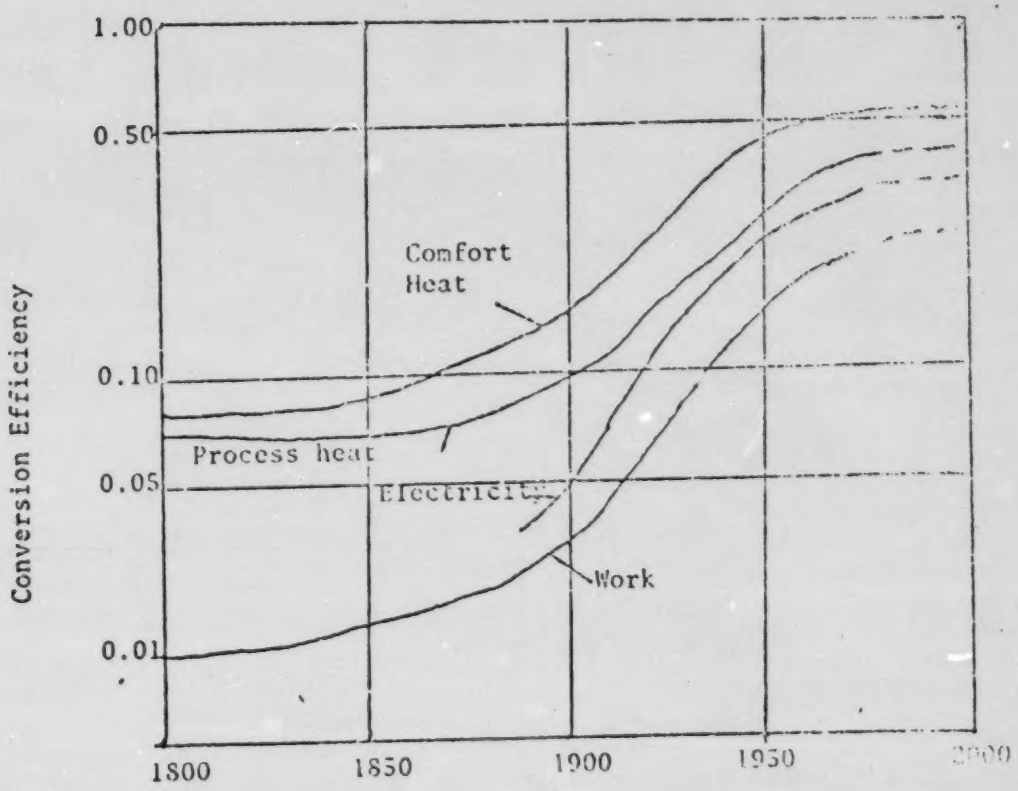


Fig. (6) Conversion efficiencies by type of useful energy output. The dotted lines are projections to 2000. (Source: Chauncey Starr, "Energy and Power", Sci. Amer. Vol. 224, p. 40 (Sept. 1971)

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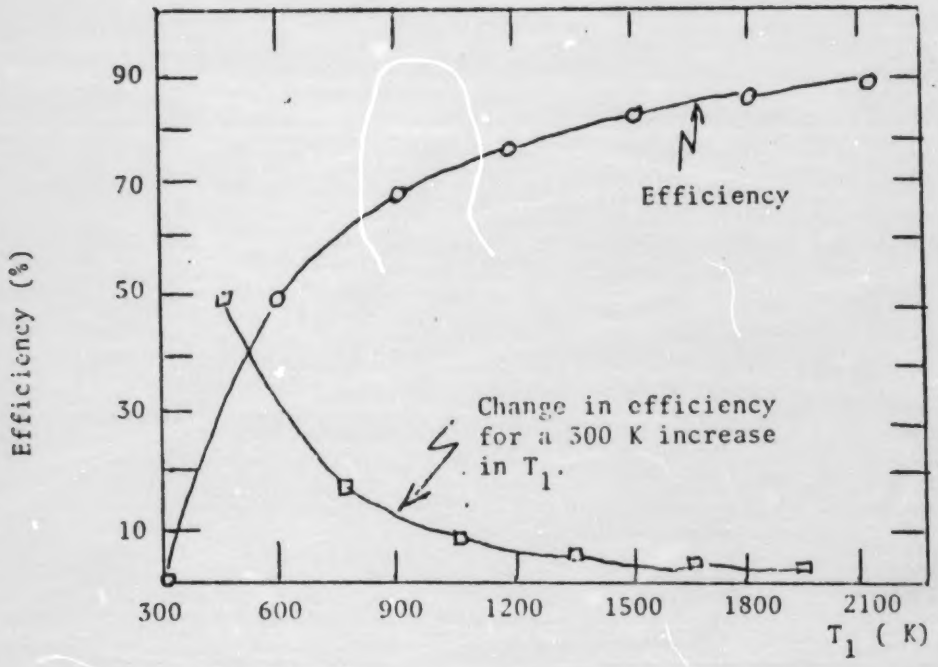


Fig. (7) Efficiency and change in efficiency for a Carnot engine assuming T_0 = 300°K. (Source: J. Priest, Energy for a Technological Society, Addison-Wesley, Reading, Mass., 1975).

between 300°K and 1500°K, but a change in T_1 from 1200°K to 1500°K produces only a 5% increase in efficiency. Thus, the reward in increased Carnot efficiency is small even though the practical problems in making a temperature increase from 1200°K to 1500°K are immense. This type of consideration underlies the small projected increases in conversion efficiencies to the year 2000 as shown in Fig. (5) and (6). These projections indicate the importance of seeking new devices and new technologies for energy conversion so as to perform the tasks necessary for modern life more efficiently.

h. Limitations in the Application of First-Law Efficiency

The first-law efficiency is useful at keeping track of energy flows since it

is based on the first law (conservation of energy). Thus, the first-law efficiency can be used to keep track of production, usage, and waste of energy on a regional, national, and global level. Also, first-law efficiency can be used to compare energy conversion devices of a particular type. Used in this way, the first-law efficiency can help in the selection of an energy conversion device from a group of devices of a particular type so as to minimize energy input. Based on these considerations, the first-law efficiency will continue to be a viable concept in the field of energy conversion.

However, the first-law efficiency is somewhat inadequate as an indicator of possible fuel savings. The limitations of first-law efficiency can be classified as follows:

* The maximum value of the first-law efficiency depends on the device and temperatures; it may be greater than, less than, or equal to 1;
* The first-law efficiency reflects losses in the quantity of energy and not losses in the quality of energy. That is, the degredation of energy is not represented by the first-law efficiency;
* The first-law efficiency cannot be readily generalized to complex energy conversion systems in which the useful output is some combination of work and heat.

In order to obtain additional insights into possible fuel savings due to more efficient use of energy, other indicators of energy conversion efficiency have

been defined and applied to various energy conversion systems. The next section treats one of these other indicators of energy conversion efficiency, called second-law efficiency.

i. Problems

PROBLEM 1: A Carnot engine is operated between two heat reservoirs at 900°K and 300°K. If the engine absorbs 1000 BTU from the heat reservoir at 900°K, calculate the heat exhausted to the heat reservoir at 300°K and the useful work done.

PROBLEM 2: A Carnot refrigerator is operated between two heat reservoirs at 200°K and 300°K. If the engine absorbs 1000 BTU of electrical energy, calculate the heat absorbed from the heat reservoir at 200°K and the heat exhausted to the heat reservoir at 300°K.

PROBLEM 3: Carry through the algebraic steps to obtain the expression for η_{MAX} for each of the following devices: electric refrigerator or air conditioner; electric heat pump; heat-powered heating device; and the absorption refrigerator.

PROBLEM 4: The total energy used for transportation in 1973 amounted to 19×10^{15} BTU of which 16.1×10^{15} BTU was wasted as exhaust, etc. What was the average first-law efficiency of energy conversion in the transportation sector for 1973? Suppose that the

average first-law efficiency were increased to 0.20. How much less energy would have been used by transportation in BTU? If the price of imported oil averaged $13.20 per barrel, how much less would the U.S. have had to pay for imported oil in 1973? One barrel of oil yields approximately 5.8×10^6 BTU.

PROBLEM 5. Suppose that a heat pump was being driven by a Diesel engine, and this energy conversion system was used to heat a home. Let the high temperature of the diesel engine be 1700°K (2600°F). Furthermore, suppose this heat-powered heating device is used to heat a building to 294°K (70°F) when the outdoor temperature is 275°K (35°F). What is the maximum COP (η_{MAX}) for this device? Let the actual COP of the device be 1.0. The Diesel engine uses fuel with a heat of combustion of 1.4×10^5 BTU per gallon. Suppose the heating requirement of the building is 1.4×10^6 BTU per hour. How many gallons of oil are required to heat the building for 10 hours? How many gallons of oil are required in an oil furnance with a first-law efficiency of 0.65 is used?

PROBLEM 6 The spent steam in a large industrial plant is used to operate an absorption refrigerator. Let the temperature of the spent steam be 378°K (221°F). Suppose the interior of the refrigerator is 278°K (41°F) while the surrounding environment in the plant is 300°K (79°F).

What is the maximum COP of this absorption refrigerator? Let the actual COP = 0.75 for an absorption refrigerator operating under the temperature conditions above. How many BTU are transferred from the cold compartment for every 1000 BTU of heat absorbed from the spent steam?

PROBLEM 7 Carry out the calculations necessary to obtain Fig. (7).

j. Solution to Problems

PR: 1 The Carnot efficiency is 1 - 300/900 = 2/3. The useful work done is (2/3) (1000 BTU) = 667 BTU. The heat exhaust is, therefore, 1000 BTU - 667 BTU = 333 BTU.

PR: 2 The COP of the Carnot refrigerator is

$$1/(\frac{300}{200}) - 1) = 2.$$

The heat absorbed from the heat reservoir at 200°K is (2) (1000 BTU) = 2000 BTU. The heat exhausted to the heat reservoir at 300°K is 1000 BTU + 2000 BTU = 3000 BTU.

PR: 3. $\eta = \frac{Q_3}{Q_0 - Q_3} = \left(\frac{Q_0}{Q_3} - 1\right) - 1$, for the electric refrigerator or air conditioner.

But, $\frac{Q_0}{Q_3} = \frac{T_0}{T_3}$, when ΔS_T and ΔS of the device are zero.

So, $\eta_{MAX} = \left(\frac{T_0}{T_3} - 1\right) - 1$ (Electric Refrigerator or Air Conditioner)

The heat-powered heating device has an efficiency given by $\eta = \frac{Q_2}{Q_1}$.

But, from the first-law of thermodynamics

$$0 = Q_2 - Q_1 + Q_0,$$

and

$$-\frac{Q_1}{T_1} + \frac{Q_2}{T_2} + \frac{Q_0}{T_0} = 0$$

when ΔS_T and ΔS of the device are zero.

Substituting for Q_0 gives:

$$-\frac{Q_1}{T_1} + \frac{Q_2}{T_2} + \frac{Q_1 - Q_2}{T_0} = 0.$$

The last equation can be easily solved for the ratio of Q_2/Q_1:

$$\frac{Q_2}{Q_1} = \left(1 - \frac{T_0}{T_1}\right) / \left(1 - \frac{T_0}{T_2}\right),$$

which yields the result for η_{MAX}. A similar method of solution yields the answers in the other cases.

4: Average first-law efficiency ε, in 1973 for transportation was

$$\varepsilon_1 = \frac{(19 - 16.1) \times 10^{15} \text{ BTU}}{19 \times 10^{15} \text{ BTU}} = 0.15$$

If the average first-law efficiency were $\varepsilon_2 = 0.20$, then the energy required for transportation is

$$2.9 \times 10^{15} \text{ BTU}/0.20 = 14.5 \times 10^{15} \text{ BTU}.$$

Thus, 4.5×10^{15} BTU less would have been required in 1973. This amounts to 4.5×10^{15} BTU/5.8×10^{6} BTU per barrel = 7.75×10^{8} barrels of oil. If all this oil were from importations, then the U.S.A. would have spent (7.75×10^{8} barrels) ($13.20 per barrel) = $10.2 billion less for imports.

PR. 5: From Table (1), the maximum COP of a heat-driven heating device is

$$\eta_{MAX} = \frac{1 - \frac{T_0}{T_1}}{1 - \frac{T_0}{T_2}},$$

$$\eta_{MAX} = \frac{1 - \frac{275}{1700}}{1 - \frac{275}{294}} = 13.0$$

The heat input to the device is given by Q_2/η = (1.4×10^{6} BTU/hr)/(1) = 1.4×10^{6} BTU/hr. The number of gallons of fuel oil is given by (1.4×10^{6} BTU/hr)(10 hr)/(1.4×10^{5} BTU/gal) = 100 gal. If an oil furnace were used, the number of gallons of oil required would be given by (1.4×10^{6} BTU/hr) (10 hr)/(1.4×10^{5} BTU/gal) (.65) = 154 gal.

PR. 6 From Table (2), the maximum COP of an absorption refrigerator is

$$\eta_{MAX} = \frac{1 - \frac{T_0}{T_1}}{\frac{T_0}{T_3} - 1},$$

$$\eta_{MAX} = \frac{1 - \frac{300}{378}}{\frac{300}{278} - 1} = 2.6$$

The heat Q_3 transferred from the cold compartment is given by

$$\eta Q_1 = (.75)\ (1000\ BTU) = 750\ BTU.$$

PR. 7. The Carnot efficiency for T_1 with $T_0 = 300°K$ is given by

$$\eta_1 = 1 - \frac{300}{T_1} \quad .$$

If the high temperature is changed by 300°K to $T_1 + 300°K$, then,

$$\eta_2 = 1 - \frac{300}{T_1 + 300}$$

The change in efficiency δ due to this 300°K temperature increase is

$$\delta = \eta_2 - \eta_1 = (300)^2/T_1(T_1 + 300).$$

Then, a table can be written down from which Fig. (12) can be plotted.

T_1	η	T_1+150°K	δ
300°K	0	450°K	0.50
600	0.50	750	0.17
900	0.67	1050	0.08
1200	0.75	1350	0.05
1500	0.80	1650	0.03
1800	0.835	1950	0.025
2100	0.86		

SEGMENT II. EFFICIENCY OF ENERGY CONVERSION DEVICES: Part II

a. Definition of Efficiency: Second-Law Efficiency or Effectiveness

Several authors have recently proposed alternative quantities which can be used as an efficiency to obtain insight into potential fuel savings. One of these quantities, called effectiveness or second-law efficiency, has been strongly recommended in a study sponsored by the American Physical Society in 1974.[1] This section treats second-law efficiency in detail. The second-law efficiency ε can be defined as follows:

$$\varepsilon = \frac{\text{ENERGY TRANSFER OF A DESIRED KIND}}{\text{MAXIMUM POSSIBLE ENERGY TRANSFER}}$$

Where the denominator is the maximum possible heat or work usefully transferrable for the same function by any device or system using the same energy input as the given system or device.

Some features of the second-law efficiency are:

*The numerator is the same in the first-law and second-law efficiencies;

*The denominator is different and brings the second law of thermodynamics directly into the definition;

*"Maximum" in the denominator means the theoretical maximum permitted by both the first and the second laws of thermodynamics;

*The denominator is not restricted to one device or type of device. That is, the denominator is a task maximum, not a device maximum;

*The value of ε_{MAX} is 1 in all cases.

It should be noted that $\varepsilon = 1$ only for a reversible process which must occur infinitely slowly.

39

The focussing on specific energy-using tasks in the definition of the second-law efficiency allows energy conversion devices to be compared to a general physical performance standard defined not by the device, but by the task. Thus, in the use of second-law efficiency, the specific energy-using task - providing heat to a home, providing hot water to a home, moving a vehicle, etc. - must be carefully defined before the second-law efficiency can be calculated. However, in the words of the American Physical Society report, "such analysis delineates the limitations and deficiencies of the devices we now have, and indicates where they should be improved or be replaced with new devices or integrated to form new systems which perform joint tasks more efficiently than either could separately accomplish."[1]

b. Available Work[2]

The concept of available work is useful for clarifying the role which the second law plays in determining the ways in which energy can be utilized or changed into useful work. Available work allows the quality of energy to be considered. For example, work is the highest quality energy while heat at low temperature is low quality energy. Also, unlike energy which is always constant or entropy which must increase (or be constant) in an isolated system, the available work is consumed during a process. The quantity available work is defined as the maximum work that can be performed by a system during a process which brings the system to a final state in equilibrium with the atmosphere (or environment of the system in general). The system can exchange energy with the atmosphere, but work done on the atmosphere is not counted as part of the available work. The available work can be defined for a system characterized by internal energy U, entropy S, and volume V. See Fig. (8). The system will be allowed to exchange heat Q' and work W' with the atmosphere which is at pressure P_0 and temperature T_0. The system will also be able to perform work W on other systems. This work is

the useful work done by the system. The useful work W is then given by[3]:

$$W = B - T_0 \Delta S_T$$

where

$$B = -(\Delta U + P_0 \Delta V - T_0 \Delta S),$$

and

$$\Delta S_T = \frac{Q'}{T_0} + \Delta S.$$

The work W' done on the atmosphere is replaced by $P_0 \Delta V$ in the above relations.

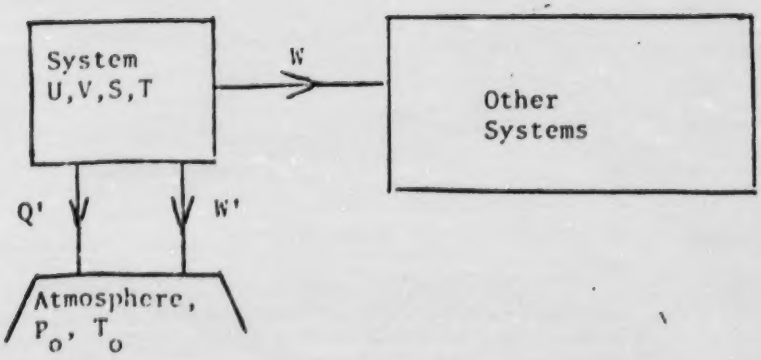


Fig. (8) Schematic diagram of a system interacting with the atmosphere and performing work on other systems. The atmosphere is a heat reservoir at pressure P_0 and temperature T_0. Other symbols are defined in text.

The total entropy change, entropy change of the atmosphere, and the entropy change of the system are given by ΔS_T, Q'/T_0, and ΔS, respectively. The terms ΔU, ΔV, and ΔS represent the changes in internal energy, volume, and

entropy, respectively, when the system comes into equilibrium with the atmosphere. Obviously, for a system in equilibrium with the atmosphere, B = 0. A physical interpretation of the quantity B can be obtained by noting that the second law of thermodynamics requires that $T_0 \Delta S_T \geq 0$. Thus, $W \leq B$, and

$$W_{MAX} = B.$$

That is, the maximum work that can be performed by the system is equal to B. Hence B must be the available work. Also, for a given task which requires a certain work W, the minimum available work to perform the task is $B_{min} = W$. This condition occurs when $\Delta S_T = 0$, so that the process is reversible. Finally, it should be noted that the amount of available work is reduced by $T_0 \Delta S_T$ during a process. The term $T_0 \Delta S_T$ is called the unavailable work or the irreversibility.[4] In other words, the energy that becomes unavailable for work during an irreversible process is T_0 times the total entropy change of system and its surroundings. Since natural processes are irreversible, energy is constantly becoming available for work in the real world. This conclusion, due to Kelvin, is known as the principle of degradation of energy.

c. Second-Law Efficiency in Terms of Available Work.

The numerator in the definition of second-law efficiency is just the useful energy transfer or output. In the case where the useful energy transfer is work W, then we can write

$$W = B - T_0 \Delta S_T.$$

The maximum possible energy transfer in the denominator must occur when $\Delta S_T = 0$ so that the denominator is simply W_{MAX} which equals the available work B. Thus, in this case

$$\varepsilon = \frac{W}{B} = \frac{B - T_0 \Delta S_T}{B}$$

or

$$\varepsilon = 1 - \frac{T_0 \Delta S_T}{B} \quad .$$

This relation shows immediately that $\varepsilon = \varepsilon_{MAX} = 1$ when the unavailable work vanishes, $T_0 \Delta S_T = 0$.

The above relation can be generalized by using the fact that $W = B_{min}$, where B_{min} is the minimum available work needed to perform the task. The actual available work B will be rewritten as B_{act}. Thus, the second-law efficiency can be expressed solely in terms of available work as

$$\varepsilon = \frac{B_{min}}{B_{act}}$$

The last expression for second-law efficiency is adopted as the general expression in terms of available work. It is important to note that the initial available work is positive, and the final available work vanishes when the system is in equilibrium with its surroundings. Thus, second-law efficiency is defined in terms of a physical quantity which is actually decreased in a process as the system comes into equilibrium with its surroundings.

d. Minimum Available Work for Various Energy End Uses.

The minimum available work B_{min} can be determined for various types of energy end-use. The end-use needs to be considered rather than the type of device because of the nature of the definition of second-law efficiency. Thus, if the end-use is a work output, W_{out}, such as the turning of a shaft in a turbine, the pumping of a fluid, or the propelling of a vehicle, the minimum

available work is given by

$$B_{min} = W_{out}.$$

If the end-use is heat Q_2 added to a heat reservoir at the warm temperature T_2 such as in space heating, cooking, or drying, the minimum available work B_{min} can be found by using the results from Section I.f for the heat-pump mode of energy conversion. There, the maximum first-law efficiency η_{MAX} was given by

$$\eta_{MAX} = \left(\frac{Q_2}{\text{Energy Input}}\right)_{MAX} = \frac{1}{\left(1 - \frac{T_0}{T_2}\right)}$$

For a given heat output Q_2, the denominator must be the minimum energy input so that $\eta = \eta_{MAX}$. but, the minimum energy input is just the minimum available work so that

$$B_{min} = Q_2 \left(1 - \frac{T_0}{T_2}\right).$$

If the end-use is heat Q_3 extracted from a heat reservoir at the cool temperature T_3 such as in refrigeration or air conditioning, the minimum available work B_{min} can be found by using the results from Section I.f for air-conditioner mode of energy conversion. There, the maximum first-law efficiency η_{MAX} was given by

$$\eta_{MAX} = \left(\frac{Q_3}{\text{Energy Input}}\right)_{MAX} = \frac{1}{\left(\frac{T_0}{T_3} - 1\right)}$$

For a given amount of extracted heat Q_3, the denominator must be the minimum energy imput so that $\eta = \eta_{MAX}$. Therefore, the minimum available work is given by

$$B_{min} = Q_3 \left(\frac{T_0}{T_3} - 1 \right) .$$

These results are summarized in Table (3).

e. Actual Available Work for Various Energy Sources

The actual available work B_{act} from various types of energy sources can be determined in general. As in the case of end-use, the energy source needs to be considered rather than the type of device. Thus, if the energy from the source is a work input, W_{in}, such as water power, wind power, raised weight, etc., the actual available work is given by $B_{act} = W_{in}$. In the case of a fuel with heat of combustion ΔH, actual available work is approximated as $B_{act} \simeq \Delta H$. This approximation is usually good to within a 10% error.
The difference between B_{act} and ΔH is due to the fact that the combustion flame is not a perfect heat reservoir since the flame temperature does not remain constant.[5]

If the source is a heat reservoir at a high temperature T_1, which provides heat Q_1, then the actual available work B_{act} can be found by using the results from Section II.f for a heat engine. There, the maximum first law efficiency η_{MAX} was given by

$$\eta_{MAX} = \left(\frac{\text{Work Output}}{Q_1} \right)_{MAX} = 1 - \frac{T_0}{T_1} .$$

For a fixed heat input Q_1, the numerator must be the maximum work output so

	WORK W_{IN}	FUEL WITH HEAT OF COMBUSTION $\lvert\Delta H\rvert$	HEAT Q_1 FROM HOT RESERVOIR AT T_1
SOURCES	(e.g., water power, wind power, raised weight)[or electricity if the wall socket is treated as the source]	(e.g., coal, oil, gas)	(e.g., goethermal source, solar collector source) [also fission reactors and fossile-fuel plants if alternatives to thermal operation are excluded]
	$B = W_{IN}$	$B \equiv \Delta H^a$ (usually to within 10%)	$B = Q_1(1 - \frac{T_0}{T_1})$
	WORK W_{OUT}	HEAT Q_2 ADDED TO WARM RESERVOIR AT T_2	HEAT Q_3 EXTRACTED FROM COOL RESERVOIR AT T_3
END USES	(e.g., turning shafts, pumping fluids, propelling vehicles)	(e.g., space heating, cooking, baking, drying)	(e.g., refrigerating, air conditioning)
	$B_{min} = W_{OUT}$	$B_{min} = Q_2 (1 - \frac{T_0}{T_2})$	$B_{min} = Q_3(\frac{T_0}{T_3} - 1)$

a. An exact consideration is required for each fuel.

Table (3). Available work provided by sources and needed by end users. $T_1 > T_2 > T_3$ (Source: "Efficient Use of Energy, A Physics Perspective." ed. by W. Carnahan et. al., in Efficient Energy Use, American Institute of Physics, New York 1975).

that $\eta = \eta_{MAX}$. Therefore, the actual available work is given by

$$B_{act} = Q_1 \left(1 - \frac{T_0}{T_1}\right)$$

These results are also summarized in Table (3).

The last equation for B_{act} provides an example of the concept of quality of energy. For a specific amount of heat Q_1 transferred from the high temperature reservoir, the actual available work increases as the temperature T_1 increases. In general, the greater the available work from an energy source, then the greater is the quality of energy from that source. So heat Q_1 available from a reservoir at a given temperature is higher quality energy than the same amount of heat available from a reservoir at a lower temperature. For example, a given amount of heat at high temperature in the main steam line of an electric power plant is higher quality energy than an equal amount of heat at a lower temperature in the coolant water for the condenser. Another example is the wet cell (automobile battery): the available work from a charged, cooled battery is greater than that of a discharged battery having the same total energy content because it is hot. Thus, the chemical energy in the charged, cooled battery is higher quality energy than the heat available from the discharged, heated battery.

f. Second-Law Efficiency for Single Source - Single Output Devices.

To determine the second-law efficiencies ε for various single-source single-output devices, it is only necessary to divide one of the end-use entries for B_{min} by one of the source entries for B_{actual} in Table (3). The results are shown in Table (4) for the 9 possible devices. The results are expressed in terms of first-law efficiencies for a comparison. Examples

of the devices are also included in Table (4). As a sample calculation, the detailed analysis leading to the result in square 6 (solar hot water heater) proceeds as follows.

The first-law efficiency is a COP given by

$$\eta = \frac{Q_2}{Q_1}$$

The second-law efficiency is given by

$$\varepsilon = \frac{B_{min}}{B_{act}}$$

where

$$B_{min} = Q_2\left(1 - \frac{T_0}{T_2}\right),$$

and

$$B_{act} = Q_1\left(1 - \frac{T_0}{T_1}\right).$$

The last four relations can be combined to give

$$\varepsilon = \eta\left(\frac{1 - \frac{T_0}{T_2}}{1 - \frac{T_0}{T_1}}\right),$$

which is the expression in Table (4).

END USE \ SOURCE	Work W_{IN}	Fuel: Heat of combustion ΔH Available work B	Heat Q_1 from hot reservoir at T_1
Work W_{OUT}	1. $\eta = W_{OUT}/W_{IN}$ $\varepsilon = \eta$ (e.g., electric motor)	2. $\eta = W_{OUT}/\Delta H$ $\varepsilon = \frac{W_{OUT}}{B}\ (=\eta)$ (e.g., an internal combustion engine)	3. $\eta = W_{OUT}/Q_1$ $\varepsilon = \frac{\eta}{1 - (T_0/T_1)}$ (e.g., geothermal plant)
Heat Q_2 added to warm reservoir at T_2	4. $\eta(COP) = Q_2/W_{IN}$ $\varepsilon = \eta\ (1 - \frac{T_0}{T_2})$ (e.g., electrically driven heat pump)	5. $\eta(COP) = Q_2/\Delta H$ $\varepsilon = \frac{Q_2}{B}(1 - \frac{T_0}{T_2})$ (e.g., engine driven heat pump)	6. $\eta(COP) = Q_2/Q_1$ $\varepsilon = \eta\ \frac{1 - (T/_0T_2)}{1 - (T_0/T_1)}$ (e.g. solar hot water heater
Heat Q_3 extracted from cool reservoir at T_3	7. $\eta(COP) = Q_3/W_{IN}$ $\varepsilon = \eta(\frac{T_0}{T_3} - 1)$ (e.g., electric refrigerator)	8. $\eta(COP) = Q_3/\Delta H$ $\varepsilon = \frac{Q_3}{}(\frac{T_0}{T_3} - 1)$ (e.g., gas-powered air conditioner)	9. $\eta(COP) = Q_3/Q_1$ $\varepsilon = \eta\ \frac{(T_0/T_3) - 1}{1 - (T_0/T_1)}$ (e.g., absorption refrigerator)

Table (4) First-law and second-law efficiencies for single source-single output devices. (Source: "Efficient Use of Energy, A Physics Perspective", ed. by W. Carnahan et. al., in Efficient Energy Use, American Institute of Physics, New York, 1975.)

g. Example of Second-Law Efficiency for an Oil or Gas-fired Furnance.

An oil or gas-fired furnance is used for space heating in many homes and businesses. About 17% of U.S. fuel consumption in 1973 was used for such furnaces.[6] A typical first-law efficiency for such furnaces is $\eta = 0.6$. The furnace provides warm air at 110° ($T_2 = 316°K$). The temperature of the outside air is taken to be 32° ($T_0 = 273°K$). Assuming that the actual available work is the same as the heat of combustion of the fuel, the result in square (5) of Table (4) can be used for the second-law efficiency ε. Thus,

$$\varepsilon = \frac{Q_2}{B}\left(1 - \frac{T_0}{T_2}\right) = \eta\left(1 - \frac{T_0}{T_2}\right),$$

so that $\varepsilon = 0.082$ when $\eta = 0.6$. This example shows that there can be a considerable difference between first-law and second-law efficiencies. In addition, the very low value for the second-law efficiency indicates that significant improvement in the efficiency of space heating may be possible, while this possibility is not so apparent from the value of the first-law efficiency.

h. Example of Second-Law Efficiency for a Solar Space Heater

Solar space-heating systems are an alternative to oil and gas-fired furnances or electric heating systems in homes and businesses. A solar space heater includes a collector system (usually, flat-plate collectors), a storage system, and a fluid (or air) distribution system. A typical first-law efficiency of this entire system is $\eta = 0.40$.[7] The solar space heater provides warm air at 110° F ($T_2 = 316°$ K). The temperature of the outside air is taken to be 32° F ($T_0 = 273°$ K). The temperature of the fluid in the collector system is assumed to be 160° F ($T_1 = 354°$ K). The result in square (6) of Table (4) can be used for the second-law efficiency ε,

$$\varepsilon = \eta \left(\frac{1 - (T_0/T_2)}{1 - (T_0/T_1)} \right),$$

so that $\varepsilon = 0.24$ when $\eta = 0.4$. Thus, solar space-heating systems not only use an abundant energy source, but also operate at significantly higher values of second-law efficiency than do conventional furnaces.

i. References and Footnotes

1. See the following reference for a complete discussion of second-law efficiency and many applications: W. Carnahan, K. W. Ford, A. Prosperetti, G. I. Rochlin, A. H. Rosenfeld, M. H. Ross, J. R. Rothberg, G. W. Seidel, and R. H. Socolow, "Efficient Use of Energy, A Physics Perspective", in Efficient Energy Use, American Institute of Physics, New York, 1975.
2. The concept of available work has been extensively discussed in the literature of thermodynamics. See, for instance, the following books: J. H. Keenan, Thermodynamics, John Wiley, New York, 1948; J. H. Keenan, E. P. Gyftopoulos, and G. H. Hatsopoulos, "The Fuel Shortage and Thermodynamics", in Proceedings of the MIT Energy Conference, MIT Press, Cambridge, Mass., 1973; K.C. Rolle, Introduction to Thermodynamics, Charles E. Merrill, Columbus, Ohio, 1973. Note that available work is sometimes referred to as availability in the literature.
3. This expression does not include a term for the diffusion of components of a system into the atmosphere. Associated with the process of diffusion is an entropy of mixing that adds another term to the available work: See the following reference for a discussion: W. Carnahan et al., "Efficient Use of Energy. A Physics Perspective", in Efficient Energy Use, American Institute of Physics, New York, 1975.

4. M. W. Zemansky, Heat and Thermodynamics, McGraw-Hill, New York 1957, pp. 186-189.

5. See Carnahan et al, Ref. 1, for a complete discussion of the difference between B_{act} and ΔH. The heat of combustion ΔH is taken as positive.

6. R. H. Romer, Energy: An Introduction to Physics, W. H. Freeman and Co., San Francisco, 1976, Appendix 2.

7. J.A. Duffie and W. A. Beckman, Solar Energy Thermal Processes, Wiley-Interscience, New York, 1974, p. 149.

j. Problems

PROBLEM 1: Calculate the available work for the Carnot engine described in Problem 1 of Section I.

PROBLEM 2: Calculate the available work for the Carnot refrigerator described in Problem 2 of Section I.

PROBLEM 3: Carry out the algebraic steps necessary to obtain the entry for ϵ in each square of Table (4).

PROBLEM 4: A geothermal electric power plant uses natural steam at 525° K (485° F) to operate a steam turbine. The first-law efficiency of the steam turbine is 0.15. If the steam is used in the turbine down to 355°K (180°F), what is the second-law efficiency of the geothermal electric power plant? Neglect any waste energy created by the electric generator.

PROBLEM 5: What is the second-law efficiency of the absorption refrigerator in Problem 6 of Section I?

PROBLEM 6: Referring to the absorption refrigerator in Problem 5, what is the available work when 1000 BTU of heat are obtained

from the hot reservoir (the spent steam)? If BTU are absorbed from the cool compartment of the refrigerator (cold reservoir), what is the minimum amount of available work which would be needed to perform this task? From the above results, calculate the second-law efficiency and compare this result with that of Problem 5.

k. Solutions to Problems

PR: 1. The available work B of the Carnot engine is given by

$$B = (1000 \text{ BTU}) \left(1 - \frac{300}{900}\right) = 677 \text{ BTU}.$$

PR. 2. The available work B of the Carnot refrigerator is given by

$$B = Q_3\left(\frac{T_0}{T_3} - 1\right) = (2000 \text{ BTU}) \left(\frac{300}{200} - 1\right),$$

$$B = 1000 \text{ BTU}.$$

PR.3 Use the method of calculation shown on the bottom of page 36. The steps in the calculation are as follows:

*Write down the definition of η from Table (3) in terms of input and output.

*Use Table (4) to express B_{min} and B_{act} in terms of the input and output quantities.

*Combine the expressions for η, ε, B_{min}, and B_{act} to express ε in terms of η.

PR. 4 The first-law efficiency is $\eta = 0.15$. From square 3 of Table (4), the second-law efficiency is given by

$$\varepsilon = \frac{\eta}{1 - \frac{T_0}{T_1}}$$

where $T_1 = 525°K$ and T_0 must be ambient temperature. Thus,

$$\varepsilon = \frac{0.15}{\left(1 - \frac{300}{525}\right)} = 0.45.$$

PR. 5. The first-law efficiency (COP) is $\eta = 0.75$. From square 9 of Table (4), the second-law efficiency is given by

$$\varepsilon = \eta \cdot \frac{(T_0/T_3)}{1 - (T_0/T_3)},$$

where $T_1 = 378°$ K, let $T_0 = 300°$ K, and $T_3 = 278°$ K. Thus,

$$\varepsilon = (0.75)\frac{(300/278) - 1}{1 - (300/378)},$$

$$\varepsilon = 0.28.$$

PR. 6. The available work B_1 when 1000 BTU are obtained from the spent steam is given by

$$B_1 = Q_1\left(1 - \frac{T_0}{T_1}\right)$$

where $Q_1 = 1000$ BTU, $T_0 = 300°K$, and $T_1 = 378°K$.

Then,

$$B_1 = 1000 \text{ BTU } \left(1 - \frac{300}{378}\right),$$

$$B_1 = 206. \text{ BTU}$$

The minimum available work B_3 which is required to extract 750 BTU from the cold compartment of the refrigerator is given by

$$B_3 = Q_3\left(\frac{T_0}{T_3} - 1\right)$$

where $Q_3 = 750$ BTU, $T_0 = 300°K$, and $T_3 = 278°K$.

Then,

$$B_3 = 750 \text{ BTU } (\frac{300}{278} - 1),$$

$$B_3 = 59.3 \text{ BTU}.$$

Obviously, $B_1 = B_{act}$ and $B_3 = B_{min}$ so

that

$$\varepsilon = \frac{B_3}{B_1} = \frac{59.3}{206.} = 0.29 .$$

SEGMENT III. ENERGY CONVERSION EFFICIENCY AND FUEL CONSERVATION

a. Efficiency of Energy Conversion Systems

An energy conversion system is a series of energy conversion devices arranged so that the energy output from one device becomes the energy input to the second device. It is easy to show that, for such a system of energy conversion devices, the first-law efficiency and second-law efficiency for the total system are simply the product of the individual efficiencies. So if η and ε represent the total system efficiencies, and η_i and ε_i represent the efficiences of the individual devices, then $\eta=\eta_1\eta_2\eta_3\cdots$ and $\varepsilon=\varepsilon_1\varepsilon_2\varepsilon_3\cdots$.

It should be noted that the useful energy output for each of the devices and the system is assumed to be of one type. That is, it is assumed that the waste energy or heat exhaust is not put to use for any of the devices.

In the case where the waste energy or exhaust is put to use from one or more of the devices, then the total system efficiency will not have the simple form above. For example, a heat pump may be driven by an engine with some of the heat exhaust from the engine added to the useful heat output of the heat pump. Then, the total system second-law efficiency can be written as

$$\varepsilon=\varepsilon_1\varepsilon_2 + (1-\varepsilon_1)\,[1 - T_0/T_2],$$

where ε_1 and ε_2 are the second-law efficiencies of the engine and heat pump, respectively.[1] The ambient temperature is T_0, and temperature of the heat reservoir to which the useful heat output is transferred is T_2.

Energy conversion devices and systems where the useful energy output is of more than one type are called combined energy systems. See Section III.f and g where combined energy systems are discussed.

b. System Efficiency of an Electric Power Plant.

A fossil fuel-fired electric power plant can be viewed as being an energy conversion system including a furnace and boiler, a steam turbine, and an electric generator arranged so that the energy output of one device becomes the energy input of the next device. If η_1, η_2, and η_3 represent the first-law efficiencies for the furnace-boiler, steam turbine, and electric generator, respectively, then the first-law system efficiency of the electric power plant is $\eta = \eta_1\eta_2\eta_3$. Typical values are $\eta_1 = 0.88$, $\eta_2 = 0.47$, and $\eta_3 = 0.99$ so that $\eta=0.41$. The average first-law efficiency of electrical power plants today is somewhat less than 0.41 because of the use of older, less-efficient steam turbines in fossil fuel plants, and because of lower steam temperatures in nuclear plants necessitated by safety requirements. Thus, the average first-law system efficiency for all electrical power plants will be taken to be $\eta = 0.33$.

The second-law efficiency of the furnace-boiler can be found by considering this energy conversion device to result in heat being transferred from the high-temperature flame to the steam. Thus, from square (5) in Table (4),

$$\varepsilon_1 = \eta_1\left(1 - \frac{T_2}{T_1}\right)$$

where $T_1 = 2273°$ K (flame temperature) and $T_2 = 823°$ K (high steam temperature). The second-law efficiency of the turbine can be found from

square (3) of Table (4),

$$\varepsilon_2 = \frac{\eta_2}{\left(1 - \frac{T_0}{T_2}\right)}$$

where T_0 = 300° K (ambient temperature). The second-law efficiency of the electric generator is given in square (1) of Table (4),

$$\varepsilon_3 = \eta_3$$

Thus, the second-law system efficiency of the fossil-fueled power plant is given by

$$\varepsilon = \varepsilon_1\varepsilon_2\varepsilon_3 = \eta \left(\frac{1 - \frac{T_2}{T_1}}{1 - \frac{T_0}{T_1}} \right).$$

This yields the results that

$$\varepsilon \simeq \eta = 0.33,$$

which is adopted as the average second-law system efficiency for all electric power plants presently in operation. Thus, the first and second-law efficiencies for electric power plants are roughly the same.

c. Improvement in the Efficiency of Electric Power Plants.

Although it will be seen in Section III.g that the second-law efficiency of electric power generation is one of the more efficient energy conversion processes in the U.S. economy, much effort is being exerted to improve this efficiency. These efforts include the development of gas turbines to be used in conjunction with steam turbines in coal-fired electric power plants; the development of magnetohydrodynamic (MHD) generators for use in both nuclear and coal-fired plants; and fuel cells with power outputs in the Megawatt range for electric power plants using methane, hydrogen, or liquid fuels.[2]

The gas turbine and MHD generator are heat engines, so they are subject to the limitations of the second law of thermodynamics. These devices will allow the use of higher temperatures T_1 and will be used in series in order to improve the first-law efficiency of electric power generation to 50-60%

Fuel cells are not heat engines so they are not subject to the same limitations of the second law of thermodynamics as have been discussed in Sections I and II. Although conversion efficiencies of present fuel cells are lower than steam turbines, the goals in fuel cell development are to reach 45% efficiency by 1985 and 60% efficiency by the 1990's.

The underlying physical principles of gas turbines, MHD generators and fuel cells are explained quite well in the article in Scientific American by C.M. Summers.[2] The latest trends in the development of these devices and systems using these devices are reported in detail in the Annual Review of Energy, Vol. I, by E. V. Somers and D. Berg.[3] Further discussion of the above devices is beyond the scope of this module.

d. System Efficiency for Air Conditioning or Refrigeration.

The air conditioning system must include the original source of energy when calculating system efficiencies. In the case of an electrical air conditioner, this means the electric power plant. (The efficiency of electrical transmission will be neglected although it is not necessarily small since up to 15% of the electrical energy can be lost during transmission). The ambient temperature near a refrigerator coil is taken to be T_0 = 300° K (81° F). The average temperature inside freezers and refrigerators is taken

to be T_3 = 265° K (18° F). If $\eta_1 \simeq 1.0$ is the first-law efficiency (COP) of the refrigerator, then square (4) in Table (4) gives

$$\varepsilon_1 = \eta_1\left(\frac{T_0}{T_3} - 1\right)$$

for the second-law efficiency of the refrigerator. If ε_2 = 0.33 is the second-law efficiency of the electrical power plant, the system efficiency ε for refrigeration is

$$\varepsilon = \varepsilon_1\varepsilon_2 = \varepsilon_2\eta_1\left(\frac{T_0}{T_3} - 1\right)$$

so that ε = 0.044.

The economics and technology of refrigerator and air-conditioner cycles are very similar so that ε = 0.044 is a reasonable value for the second-law system efficiency of air conditioning also.

e. System Efficiency for Electric Resistive Heating

The use of electric resistive heating in the home usually includes a forced-air system similar to a furnace except that electrical resistors take the place of the flame or a liquid system in which the electrical resistors are immersed in a liquid (usually a mixture of water and ethylene glycol). In both systems, the heat enters the room as warm air at a temperature T_2 = 316°K (110°F). Thus, the second-law efficiency of the electrical resistive heating system can be written

$$\varepsilon_1 = \eta_1\left(1 - \frac{T_0}{T_2}\right)$$

where the first-law efficiency η_1 = 0.9 for the electrical heating. If an ambient temperature T_0 = 273° K (32° F) is used, then ε_1 = 0.122. If ε_2 = 0.33 is the second-law efficiency of the electrical power plant, the

second-law system efficiency ε for heating is $\varepsilon = \varepsilon_1\varepsilon_2 = 0.040$. It should be noted that the second-law system efficiency of electrical resistive heating is about one-half of the second-law efficiency for a furnace obtained in Section II. g. Also, the first-law system efficiency for electric resistive heating is $\eta = \eta_1\eta_2 = 0.3$, which is much larger than the second-law system efficiency. Thus, using the high quality electrical energy to provide low temperature heat is very wasteful of available work.

f. Combined Energy Systems

A combined energy system is one in which the useful energy transfer is of two (or more) distinct types. In the case which will be treated in this section, the combined energy system results in the transfer of electricity and low-temperature heat. The low-temperature heat is generated as waste heat from a fuel consuming device which drives an electric generator. Low-temperature heat is defined to be heat delivered at about 533° K (500° F) or less. For space heating, the temperature at the register is usually about 316° K (110° F). For hot water, the temperature of the water is usually about 323° K (120° F). For industrial process steam, temperatures are usually much below 533° K (500° F) with 394° K (250° F) being representative. The amount of fuel used in the U.S. for electricity, air conditioning, and low-temperature heat is large. Estimates of the amount of fuel used in the U.S. for electricity and low-temperature heat range between 65% and 70%.[4] Combined energy systems offer promise to cut into this major usuage of fuel.

As an example, the second-law efficiency of a combined energy system suitable for space heating is analyzed. The combined energy system is comprised of a

fuel-consuming engine which drives an electric generator to produce electricity with part of the low-temperature heat from the engine exhaust transferred for space heat. See Fig. (9).

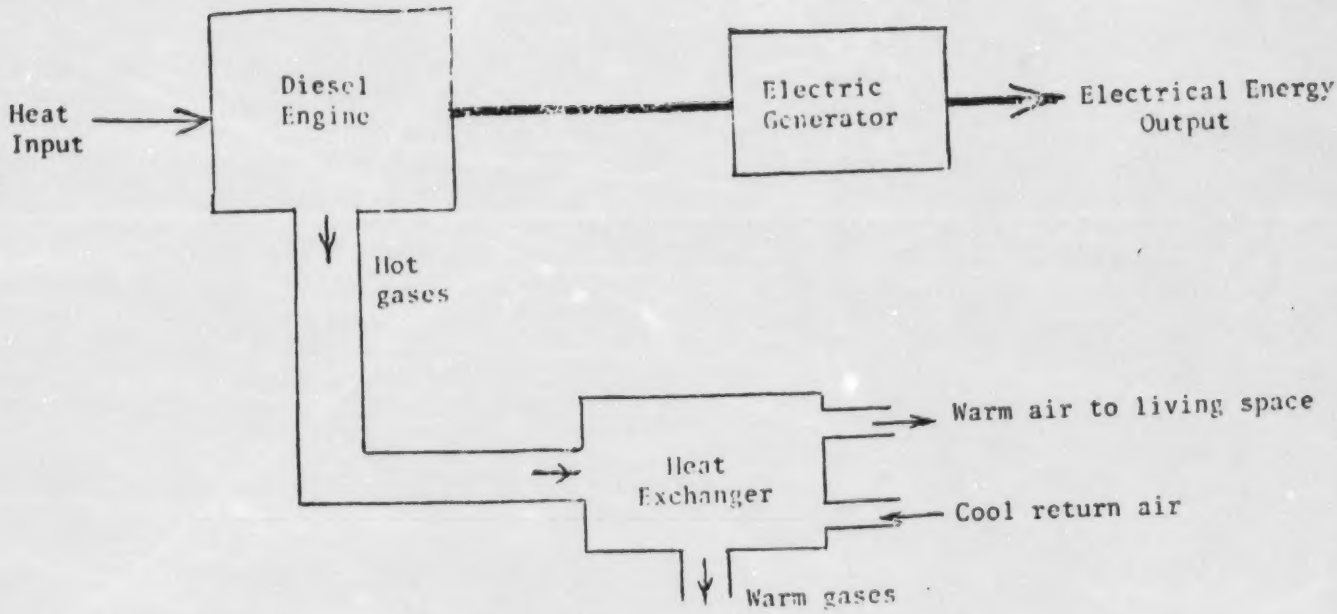


Fig. 9

Schematic diagram of a Diesel engine-electric generator system for combined production of electricity and space heat.

Let the heat input to the engine be designated by the heat of combustion ΔH for a unit of fuel. Also, let f_1 and f_2 represent the fractions of ΔH delivered as electricity and low-temperature heat respectively. Thus, $W_{out} = f_1 \Delta H$ where W_{out} is the electrical energy output, and $Q_2 = f_2 \Delta H$ where Q_2 is the useful heat output from the engine exhaust to a reservoir at temperature T_2. The total, minimum available work B_{min} to provide this useful energy output can be found by adding the expressions for B_{min} from the first two columns at the bottom of Table (3):

$$B_{min} = W_{out} + Q_2\left(1 - \frac{T_0}{T_2}\right),$$

or

$$B_{min} = f_1 \Delta H + f_2 \Delta H \left(1 - \frac{T_0}{T_2}\right).$$

The actual available work $B_{act} \simeq \Delta H$ so that the second-law efficiency is

$$\varepsilon = \frac{B_{min}}{B_{act}} = f_1 + f_2\left(1 - \frac{T_0}{T_2}\right), \quad \text{(Combined system)}$$

where the task is defined as providing electricity and low-temperature heat. Suppose a diesel engine drives an electric generator with a part of the exhaust used for space heating. Typical values in this example for the quantities appearing in the above expression for ε are $f_1 = 0.30$, $f_2 = 0.33$, and $T_2 = 394°K$ (250°F). Ambient temperature $T_0 = 273°K$ (0° F). Using this data gives a second-law efficiency of $\varepsilon = 0.45$ for the combined system. This value of second-law efficiency is much higher than typical values of second-law efficiency for systems currently in use. See

Table (5) on page 54. If the first-law efficiency of the combined energy system is defined as the ratio of the total useful energy transferred (i.e., the sum of the electrical output and the low-temperature heat available from the engine's exhaust) to the heat input from fuel, then it can easily be shown that the first-law efficiency η of the combined system is $\eta = f_1 + f_2$, which in the example here has the value $\eta = 0.63$.

The actual fuel savings due to a combined system can be obtained by calculating the ratio of the units of fuel required to produce separately the same amount of electricity and heat as produced by the combined system. If η_1 and η_2 are the first-law efficiencies of electricity and heat production, respectively, then the electrical output W_{out} requires W_{out}/η_1 units of fuel and the heat output Q_2 requires Q_2/η_2 units of fuel. The total amount of fuel required for separate production of the electricity and heat is

$$W_{out}/\eta_1 + Q_2/\eta_2 = \frac{f_1}{\eta_1} + \frac{f_2}{\eta_2} \Delta H \ .$$

Thus, the ratio ρ of fuel required by the separate systems to fuel required by the combined system is

$$\rho = \frac{f_1}{\eta_1} + \frac{f_2}{\eta_2} \ .$$

In the example above, if $\eta_1 = 0.33$ and $\eta_2 = 0.67$ for a Diesel engine used for small scale heat output, then $\rho = 1.4$. In other words 40% more fuel is required by the separate systems.

There are many important problems to be resolved before combined energy systems can be widely implemented. These problems include:

* Variations in the time at which electricity and heat are needed.

* The size of the heat engines presently available are more suitable for heating large buildings or groups of houses rather than a small commercial building or single-family house.

* Large variations in energy use can occur in single-family houses.

* Interfacing of the combined system with the central electric power company.

* Maintenance and repair of the combined energy system if installed in a small building or single-family house.

* Local noise and pollution control.

g. Industrial Cogeneration: An Example of a Combined Energy System.

The potential for reduced fuel use from combined energy systems in the U.S. can be further appreciated by applying the results of Section III. f. to industrial cogeneration of electricity and low-temperature process steam. The system uses a gas turbine for electricity and process steam production. The fraction $f_1 = 0.25$ for the electricity produced, and the fraction $f_2 = 0.45$ for the process steam produced. The first-law efficiency of the combined system is $\eta = f_1 + f_2$, which in the example here has the value $\eta = 0.70$. The second-law efficiency ε for the combined system can be calculated if the temperature T_2 is specified. A typical value for industrial cogeneration of steam is $T_2 = 474°$ K (400° F). Then, using the result of Section III. f. gives $\varepsilon = 0.44$ for industrial cogeneration. If $\eta_1 = 0.33$ for electricity production and $\eta_2 = 0.55$ for steam production for separate systems, then the ratio ρ for fuel required by the separate

systems to fuel required by the combined system is

$$\rho = \frac{f_1}{\eta_1} + \frac{f_2}{\eta_2} = 1.60$$

Thus, 60% more fuel is required by the separate systems! See Fig. 10 for a schematic representation of the gas turbine system for industrial cogeneration.

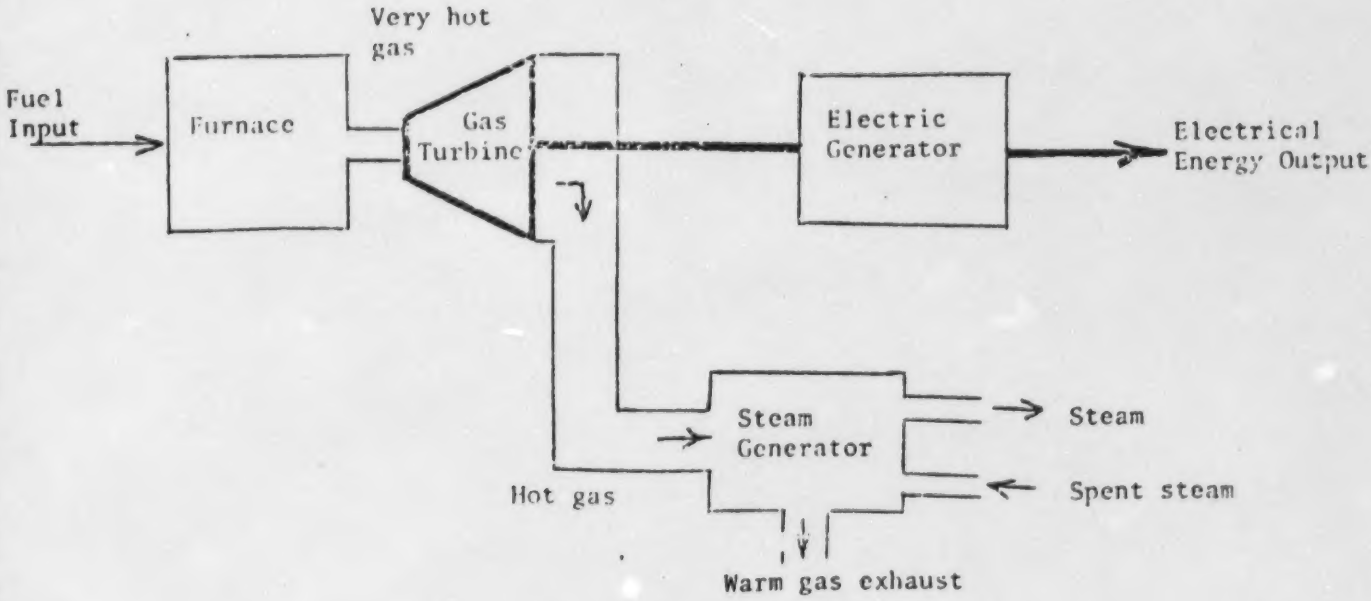


Fig. 10

Schematic diagram of a gas turbine - electric generator system for co-generation of electricity and process steam.

Roughly 17% of U.S. fuel consumption is used for industrial process steam

and 26% for electrical generation.[4] In 1973, the total U.S. fuel consumption in terms of equivalent heat content amounted to 71.9×10^{15} BTU. Thus, 12.2×10^{15} BTU of U.S. fuel consumption in 1973 was used to produce electricity. If one-half of the process steam used by industry have been provided by cogeneration using the type of system discussed in this Section, this would have resulted in a national fuel savings of 32% (3.9×10^{15} BTU) for electricity or 8% in total fuel consumption. The details of the computation yielding the above results are given in Section IV. b.

h. Conclusion: The Potential for Fuel Conservation

Second-law efficiencies for various representative energy consuming activities throughout the U.S. economy are listed in Table (5). The values in Table (5) differ somewhat from the similar values calculated above because of more realistic conditions imposed on the calculations leading to Table (5). The results in Table (5) show that, for most activities in the residential and commercial sector of the U.S. economy, second-law efficiencies are less than 0.10, clear indications that energy is being used inefficiently today. It should also be noted that, contrary to the popular conception, electric power generation is one of the more efficient conversion processes in the U.S. economy at present. It is only when electrical energy is used to include end-uses especially wasteful of available work (like electrical resistive space heating) rather than end-uses which make good use of available work (like electrical motors) that the system efficiency is very low.

It can be seen that considerable improvement can be made in second-law

efficiencies, bringing about a significant savings in fuel. Ross and Williams[5] have used the data in Table (5) together with other similar data to conclude that the 1973 living standard of the U.S. could have been provided with about 40% less energy.

Energy-consuming Activities (Current technology)	Second-law Efficiency
Residential and Commercial	
Space heating:	
Fossil-fuel fired furnace	0.05
Electric resistive	0.025
Air Conditioning	0.045
Water heating:	
Gas	0.03
Electric	0.015
Refrigeration	0.04
Transportation	
Automobile	0.09
Industrial	
Electric power generation	0.33
Process-steam production	0.33
Steel production	0.23
Aluminum production	0.13

Table (5) Second-law efficiencies for energy consuming activities. (Source: Ross and Williams, "The Potential for Fuel Conservation", Perspectives on Energy, Oxford Univ. Press, New York, 1978 p. 526.)

Nearly 60% of the potential savings lies in four areas: space heating and cooling, the automobile, industrial cogeneration of steam and electricity, and

commercial lighting. Ross and Williams provide detailed suggestions on how these improvements can be brought about. Several of the suggestions include using the energy conversion system to provide more than one form of useful energy output. Industrial cogeneration of steam and electricity, for example, refers to when high-quality, high-temperature energy available from combustion is first used to generate electricity so that the low-temperature, spent steam from the turbine can be applied for process steam applications. The second-law efficiency for industrial cogeneration is between 0.40 and 0.45. Combined systems providing space heat and electricity for homes and businesses are also possible. The second-law efficiency of this combined system is 0.45. Both industrial cogeneration and combined energy systems for space heat and electricity were given as examples earlier in this Section. Using such systems, Ross and Williams estimated that electricity consumption in 1973 could have been reduced by 30%, while central-station electric power generation could have been reduced by 60% because of the large amount of electrical power generated by industrial cogeneration and combined energy systems in the residential and commercial sectors.

Thus, the concepts of energy and energy conversion efficiency presented in this module demonstrate opportunities for significant decreases in fuel consumption arising from both efficiency improvements and task modifications. The reader is referred to other sources for further study.[6]

i. References and Footnotes

1. See "Efficient Use of Energy, A Physics Perspective", in Efficient Energy Use, AIP, New York, 1975.

2. Claude M. Summers, "The Conversion of Energy", in Scientific American, Vol. 224, No. 3, p. 148, September 1971.

3. E.V. Somers and Daniel Bery, "Advanced Energy Conversion", in Ann. Rev. Energy, Vol. 1, p. 345, 1976.

4. Joan Ross and Marc Ross, 'Some Energy Problems and Solutions", in The Physics Teacher, p. 272, May 1978; R. H. Romer, Energy: an Introduction to Physics, W. H. Freeman and Co., San Francisco, 1978, Appendix L, p. 600.

5. M. Ross and Williams, "The Potential for Fuel Conservation", reprinted in Perspectives on Energy, Oxford Univ. Press, New York, 1978, p. 526.

6. R.H. Socolow, "The Coming Age of Conservation", Annual Review of Energy, Vol. 2, 1977, pp. 239-289; L. Schipper, "Raising the Productivity of Energy Utilization", Annual Review of Energy, Vol. 1, 1976, pp. 455-517; C.A. Berg, "Potential for Energy Conservation in Industry", Annual Review of Energy, Vol. 1, 1976, pp. 519-534. Other more technical., but still elementary, applications of related ideas can be found in M.H. Rubin, "Figures of Merit for Energy Conversion Processes", Am. J. Physics, Vol. 46, No. 6, June 1978, p. 637; H.S. Leff and W.D. Teeters, "EER, COP, and the Second Law Efficiency for Air Conditioners", Am. J. Phy., Vol. 46, No. 1, Jan, 1978, p. 19; and L. R.

Plumb, "Reversibility - Key to More Efficient Heating Devices", Am. J. Phy. Vol. 44, No. 5, May 1976, p. 485. See also E.R. Berndt in Ref. 1 of Section 0 for a detailed analysis of the economic implications of thermodynamic measures of energy efficiency. In addition, C. Summers Ref. 2, provides an account of the efficiency of energy conversion for the average reader. Summers discusses direct conversion of heat to electricity using fuel cells and magnetohydrodynamic devices.

j. Problems

PROBLEM 1: Prove that the first-law system efficiency η for a series of energy conversion devices arranged so that the energy output of one device becomes the energy input to the second device can be expressed as a product

$$\eta = \eta_1\eta_2\eta_3\cdots$$

PROBLEM 2: Prove that the second-law system efficiency ε for a series of energy conversion devices of the single input - single output type, arranged so that the output of one device becomes the input to the next device, can be expressed as a product $\varepsilon = \varepsilon_1\varepsilon_2\varepsilon_3\cdots$ (This is a difficult problem. The solution can be skipped and only the result used if desired.)

PROBLEM 3: Assume the task of air conditioning is defined as providing air at 286° K (55° F) to the interior of the house on a summer day. Furthermore, assume the ambient outdoor temperature is 305° K (90° F). Suppose the COP of an electrically-powered refrigerator is 2.0. Calculate the first-law and second-law system efficiencies, respectively, for this air conditioning system.

PROBLEM 4: Assume the task of heating a building is defined as providing air at 310° K (110° F) to the rooms on a winter day with an outdoor ambient temperature of 273° K (32° F). Suppose the heated air is provided by a heat pump which is driven by an engine with no waste heat recovery. Let the COP of the heat pump be 2.5, and the

first-law efficiency of the engine be 0.33. Calculate the first-law and second-law system efficiencies.

PROBLEM 5: Assume that the engine-driven heat pump in Problem 3 is modified so that the waste heat from the engine is recovered and added to the output of the heat pump. Calculate the second-law system efficiency in this case. Use the last equation in Section III.a.

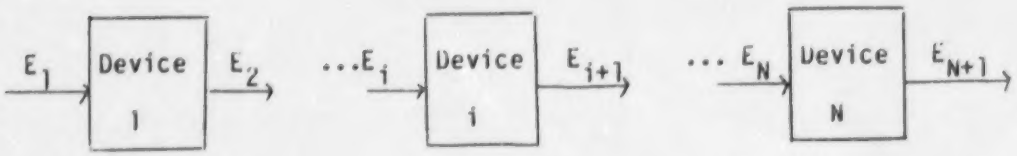
PROBLEM 6: A combined electricity and heating system for a large building uses a gas turbine and electric generator. The gas turbine has a first-law efficiency of 0.85 for heat delivery and a first-law efficiency of 0.33 for electricity. The combined system transfers a fraction 0.20 of the fuel imput as electricity and a fraction 0.70 of the fuel input as usable heat at a temperature of 473° K (400° F). What is the second-law efficiency of the combined system? What is the ratio of fuel required by separate systems to fuel required by the combined system to perform the same task? You may assume ambient temperature T_0 = 278° K (40° F).

PROBLEM 7: In 1973 about 18% of total fuel consumption in the U.S. was used for space heating in homes and businesses. Assume that combined electricity and heating systems like

the diesel engine-electric generator system described in Section III. f. are used to provide 25% of the space heat for homes and businesses. What would be the national fuel savings with this assumption? Note: See Section III. f. for any additional data.

k. Solutions to Problems

PR. 1 Consider the series of energy conversion devices labeled 1, 2, 3,...where the output from device i becomes the input to device i + 1. Let the first-law conversion efficiency of device i be η_i. Let E_i be the energy input and E_{i+1} be the energy output of device i.



(Exhaust is not shown)

Each device is of the single source-single output type. Then,

$$E_{i+1} = \eta_i E_i,$$

and the first-law efficiency for the series of devices is given by

$$\eta = \frac{E_{N+1}}{E_1}$$

But,

$$\eta = \frac{E_{N+1}}{E_N} \frac{E_N}{E_{N-1}} \frac{E_{N-1}}{E_{N-2}} \cdots \frac{E_3}{E_2} \frac{E_2}{E_1},$$

or $$\eta = \eta_N \ \eta_{N-1} \ \cdots \ \eta_2 \eta_1.$$

PR. 2. Use the same arrangement of devices as in the solution to PR. 1. Let the second-law efficiency of device i be,

$$\varepsilon_1 = \frac{B_{min,\ i}}{B_{act,\ i}}$$

The second-law efficiency of the series of devices, assumed to be of the single source - single output type, is

$$\varepsilon = \frac{B_{min}}{B_{act}}$$

where

$$B_{min} = B_{min,N}$$

and

$$B_{act} = B_{act,\,1}.$$

The energy output E_i will be either work or heat added to a warm (or hot) reservoir which in turn supplies the heat to the next device. In either case,

$$B_{min,i} = B_{act,i+1}$$

Thus,

$$\varepsilon = \frac{B_{min,\,N}}{B_{act,\,1}} = \frac{B_{min,\,N}}{B_{act,\,N}} \quad \frac{B_{act,\,N}}{B_{act,\,N-1}} \quad \frac{B_{act,\,N-1}}{B_{act,\,N-2}} \quad \cdots$$

$$\cdots \frac{B_{act,\,3}}{B_{act,\,2}} \quad \frac{B_{act,\,2}}{B_{act,\,1}},$$

$$\varepsilon = \frac{B_{min,\,N}}{B_{act,\,N}} \quad \frac{B_{min,\,N-1}}{B_{act,\,N-1}} \cdots \frac{B_{min,\,2}}{B_{act,\,2}} \quad \frac{B_{min,\,1}}{B_{act,\,1}},$$

or

$$\varepsilon = \varepsilon_N \varepsilon_{N-1} \cdots \varepsilon_2 \varepsilon_1.$$

It should be noted that it is available work which is being transferred from one device to another.

PR. 3. The first-law efficiency is given by

$$\eta = \eta_1 \eta_2 = (0.33)\,(2.0) = 0.66,$$

where $\eta_1 = 0.33$ is first-law efficiency of the electric power plant and

$\eta_2 = 2.0$,

is the COP of the refrigerator. The second-law system efficiency is

$$\varepsilon = \varepsilon_1\varepsilon_2 = \eta_1\eta_2 \frac{T_0}{T_3} - 1$$

where $T_0 = 305^0$ K and $T_3 = 286^0$ K. Thus,

$\varepsilon = 0.044$.

PR:4. The first-law system efficiency is

$$\eta = \eta_1\eta_2 = (0.33)\ (2.5) = 0.83$$

where $\eta_1 = 0.33$ is the first-law efficiency of the engine and $\eta_2 = 2.5$ is the COP of the heat pump. The second-law system efficiency ε is given by

$$\varepsilon = \varepsilon_1\varepsilon_2 \simeq \eta_1\eta_2\left(1 - \frac{T_0}{T_2}\right)$$

where $T_0 = 273°K$ and $T_2 = 316°K$. Thus,

$\varepsilon = 0.11$.

PR. 5: The second-law efficiency ε in this case is given by

$$\varepsilon = \varepsilon_1\varepsilon_2 + (1 - \varepsilon_1)\ 1 - \frac{T_0}{T_2}\ ,$$

so,

$$\varepsilon = \eta_1\eta_2 + (1 - \eta_1)\ 1 - \frac{T_0}{T_2}\ ,$$

or,

$$\varepsilon = 0.83 + (1 - 0.33)\ 1 - \frac{273}{316}\ ,$$

$\varepsilon = 0.20$.

PR. 6: The second-law efficiency ε for the combined system is given by

$$\varepsilon = f_1 + f_2\left(1 - \frac{T_0}{T_2}\right).$$

So,

$$\varepsilon = 0.20 + 0.70\left(1 - \frac{278°K}{473°K}\right),$$

and

$$\varepsilon = 0.49.$$

The ratio of fuel required by separate systems to fuel required by the combined system is

$$\rho = \frac{f_1}{\eta_1} + \frac{f_2}{\eta_2}$$

$$\rho = \frac{0.20}{0.33} + \frac{0.70}{0.85} = 1.42.$$

Thus, 42% more fuel is required by the separate systems to perform the same task as the combined system.

PR. 7: Referring to Section III. g., let $f_1 = 0.30$, $f_2 = 0.33$, $\eta_1 = 0.33$, and $\eta_2 = 0.67$ for the type of system under consideration. Then using the relations in Section III. f. gives the following result:

(Electrical energy produced by combined system) $= \frac{f_1}{f_2}\left(\frac{12.2 \times 10^{15}\,BTU}{4}\right)$

$= 2.8 \times 10^{15}$ BTU.

(Fuel required to produce electricity by separate) $= \frac{2.8 \times 10^{15}\,BTU}{\eta_1}$

$= 8.3 \times 10^{15}$ BTU.

(Percent savings in fuel for electricity) = 44%.

(Percent savings in national fuel consumption) $= \left(\frac{26}{100}\right) 44\%$

$= 11\%$

SEGMENT IV. COMPUTER ANALYSIS OF COMBINED ENERGY SYSTEMS

a. Introduction

As shown in Sec. III of this module, combined energy systems have considerably higher values of first and second-law efficiencies than do separate systems. Two examples are discussed: a diesel-electric generator system for space heat and electrical energy production and a gas turbine - electric generator system for process steam and electrical energy production (industrial cogeneration). These systems have significant potential for reducing fuel use in the U.S.

The purpose of this section is to provide a computer program which computes and graphically displays the potential for annual fuel savings in the U.S. due to the use of combined energy systems. The computer language used is Fortran. Industrial cogeneration is the specific system which is analyzed in Section IV.c. The computer program can be modified to apply to other combined energy systems by adjusting the parameters in the computer code.

b. Mathematical Model of Combined Energy Systems

Several symbols are used to denote parameters describing annual energy consumption in the U.S.:

QT = Heat equivalent of annual total fuel consumption.

WT = Total annual electric energy production.

Q1 = Heat equivalent of annual fuel consumption used for electrical energy production.

QP = Heat equivalent of annual fuel consumption used for low-temperature heat production.

QDP = Heat equivalent of energy delivered as low-temperature heat.

All of the heat and energy parameters above are expressed in the same energy units. In terms of the above parameters, one can define several dimensionless ratios:

$$R1 = Q1/QT, \quad M1 = WT/Q1,$$

$$R2 = QP/QT, \quad M2 = QDP/QP.$$

The ratios M1 and M2 are first-law efficiencies, η_1 and η_2, which are used in Sections III. f. and g. The ratios R1 and R2 are the fractions of total energy consumption used for electrical energy production and low-temperature heat production, respectively.

The following set of symbols are used to denote parameters describing the combined energy system:

DH = Heat equivalent of fuel consumed by the combined energy system.

Q2 = Heat equivalent of energy delivered as low-temperature heat by the combined energy system.

W1 = Electric energy delivered by the combined energy system.

In terms of the above parameters, the following ratios can be defined.

$$F1 = W1/DH, \quad F2 = Q2/DH.$$

The ratios F1 and F2 are the fractions f_1 and f_2 which are used in Sections III. f. and g.

The first-law efficiency MU and the second-law efficiency EPS for the combined energy system are given by

$$MU = F1 + F2, \tag{I}$$

and

$$EPS = F1 + F2\ (1 - T0/T2) \qquad (II)$$

where T0 is ambient temperature and T2 is the warm temperature at which the low-temperature heat is delivered. These expressions are derived in Sec. III. f.

Let the combined energy system provide a fraction R of the low-temperature heat. Then,

$$R = Q2/QDP.$$

Also, define P1 as the percent of electrical energy produced by the combined energy system, and P2 as the percent of total fuel consumption saved by the combined energy system. Then,

$$P1 = 100(W1/WT),$$

and

$$P2 = 100(W1/M1)/QT.$$

By algebraic manipulation, these percentages can be expressed as

$$P1 = 100\ (F1/F2)\ (R2/R1)(M2/M1)R, \qquad (III)$$

and

$$P2 = 100(F1/F2)(M2/M1)(R2)R, \qquad (IV)$$

Equations (I), (II), (III), and (IV), summarize the results of the mathematical model.

c. Sample Computer Programs

The computer program is written for the industrial cogeneration system of Sec. III. g. This industrial cogeneration system is comprised of a gas turbine and electric generator. The values of the various parameters for this system are:

F1 = 0.25, F2 = 0.45

M1 = 0.33, M2 = 0.55

R1 = 0.25, R2 = 0.17

T0 = 300 T2 = 474

The values of R1 and R2 mean that 25% of total fuel consumption went to electric energy production and 17% of total fuel consumption went to low-temperature heat for process steam. The values M1 and M2 mean that the first-law efficiencies of electric energy production is assumed to be 33%, and the first-law efficiency of process steam production is 55% using separate systems. The values of F1 and F2 mean that the industrial-cogeneration system provides 0.25 units of electric energy and 0.45 units of energy as process steam for every unit of fuel consumed. The values T0 and T2 mean ambient temperature is 300°K and the process steam is used at 474°K.

The computer program is given in Figure 11. The output for the above set of parameters is given in Figure 12. The output consists of a table of values

for the percentages P1 and P2 versus the fraction R of process steam provided by industrial cogeneration. The output also plots the values of P1 (asterisks) and P2 (plusses) versus R. The first-law efficiency MU and second-law efficiency EPS are also listed on the output.

The graph is produced using a scaling technique.[1] Since a printer can only display characters at a discrete set of positions on a line, it is not a very accurate plotter. The scaling technique uses a linear function L given by

$$L = \alpha \chi + \beta$$

where χ can take on a continuous range of values. The constants α and β are chosen so that L stays in some desired range when the variable χ varies over some specified range. The value of L is truncated using integer arithmetic, so that L can be used as a subscript of an array X. The array X has 101 elements X_1, X_2, ..., X_{101}, which are printed on one line as 101 single characters. The character " "(blank) is first stored in every element of the array X. The scaling function L is used to store some other character (for example, "+" or "*") in a particular element of the array X corresponding to the value of some variable. When the entire array is printed on a line, the position of the non-blank character corresponds to the value of the variable.

In the computer program, the variables P1 and P2 are plotted using the scaling functions

$$L1 = P1 + 1,$$

$$L2 = P2 + 1.$$

85

Thus, L1 and L2 vary from 1 to 101 as the percentages P1 and P2 vary from 0 to 100.

Each successive line of characters corresponds to a different value of the fraction R. Once the values of L1 and L2 are compiled for a specific value of R using the above two relations, the computer code prints out a line of characters which are all blanks, except for the L1th, which is an asterisk, and the L2th, which is a plus sign. Note that the first and last characters on the line are not blanks. The character " . " is stored in the elements X_1 and X_{101} of the array to make the boundaries of the graph. The positions of the asterisk and plus sign on the line are linearly dependent on the values of P1 and P2, respectively. After printing a line, the code repeats the procedure for a new value of R. After N successive lines are printed, the graph is complete.

Fig. 11
Computer Program for Industrial Cogeneration

```
00110  REAL M1, M2, N, MU
00120  DIMENSION X(101)
00130  DATA BLANK,PLUS,ASTER,DOT/" ", "+", "*", "."/
00140  READ (5, 1000)F1,F2,N,DR
00150  WRITE (6,1001)F1,F2,N,DR
00160  N1=N
00170  IF(N)50,50,20
00180  20 CONTINUE
00190  R=0.0
00200  R1=0.25
00210  R2=0.17
00220  M1=0.33
00230  M2=0.55
00240  P1=0.0
00250  P2=0.0
00260  T0=300.
00270  T2=474.
00280  MU=F1+F2
00290  EPS=F1+F2*(1.-(T0/T2))
00300  WRITE (6,1002)T0,T2,MU,EPS
00310  WRITE (6,1003)
00320  DO 30 K=1, 101
00330  30 X(K)=BLANK
00340  WRITE (6,1004)
00350  DO 40 J=1,N1
00360  X(1)=DOT
00370  X(101)=DOT
00380  L1=1.*P1+1.
00390  L2=1.*P2+1.
00400  X(L1)=ASTER
00410  X(L2)=PLUS
00420  WRITE (6,1005)R,P1,P2,(X(K),K=1,101).
00430  X(L1)=BLANK
00440  X(L2)=BLANK
00450  R=R+DR
00480  P1=100.*(F1/F2)*(R2/R1)*(M2/M1)*R
00490  40 P2=100.*(F1/F2)*(M2/M1)*R2*R
00500  WRITE (6,1004)
00505  1000 FORMAT(4F10.5)
00510  1001 FORMAT (4H F1=, F10.5,4H F2=,F10.5,3H N=,F10.5,4H DR=,F10.5)
00520  1002 FORMAT (4H, T0=,F10.5,4H T2=,F10.5,4H MU=,F10.5,5H EPS=,F10.5)
00530  1003 FORMAT (20H     R    P1         P2 /20H          *      +    )
00540  1004 FORMAT (20X,101("."))
00550  1005 FORMAT (1X,F5.2,2F6.2,2X,101A1)
00560  50 CONTINUE
00570  STOP
00580  END
```

T2= 474.00000 HU= .70000 .41519

R	F1	F2
0.00	0.00	0.00
.02	1.26	.31
.04	2.52	.63
.06	3.78	.94
.08	5.04	1.26
.10	6.30	1.57
.12	7.56	1.89
.14	8.81	2.20
.16	10.07	2.52
.18	11.33	2.83
.20	12.59	3.15
.22	13.85	3.46
.24	15.11	3.78
.26	16.37	4.09
.28	17.63	4.41
.30	18.89	4.72
.32	20.15	5.04
.34	21.41	5.35
.36	22.67	5.67
.38	23.93	5.98
.40	25.18	6.30
.42	26.44	6.61
.44	27.70	6.93
.46	28.96	7.24
.48	30.22	7.56
.50	31.48	7.87
.52	32.74	8.19
.54	34.00	8.50
.56	35.26	8.81
.58	36.52	9.13
.60	37.78	9.44
.62	39.04	9.76
.64	40.30	10.07
.66	41.56	10.39
.68	42.81	10.70
.70	44.07	11.02
.72	45.33	11.33
.74	46.59	11.65
.76	47.85	11.96
.78	49.11	12.28
.80	50.37	12.59
.82	51.63	12.91
.84	52.89	13.22
.86	54.15	13.54
.88	55.41	13.85
.90	56.67	14.17
.92	57.93	14.48
.94	59.19	14.80
.96	60.45	15.11

Page 81

Fig. 12. Computer Output for Industrial Cogeneration.

The computer program resulting in the output in Fig. 12 was run on a Control Data Corporation 6000 Series Computer System using Time-Sharing Fortran. The five digit numbers on the left represent line numbers which are equivalent to individual cards in a card deck. Statement numbers are printed after a blank which follows the line number (for example, see line 180 in Fig. (11)). The parameters R1, R2, M1, M2, T0, and T2 are specified at lines 200, 210, 220, 230, 260, and 270 respectively. The parameters F1 and F2 are read as input at line 140. The input also includes the number N of lines on the graph, and the increment DR in the value of R from one line to the next on the graph. The initial values of R, P1, and P2 are set at 0.0 at lines 190, 240, and 250, respectively. The values of R, P1, and P2 which correspond to each line of the graph are computed at lines 450, 480, 490, respectively. The values of first-law efficiency MU and second-law efficiency EPS are computed at lines 280 and 290, respectively.

d. Problems for Computer Analysis

PROBLEM 1: Load the computer program in Fig. 11 on an available computer. Run the program using the values F1 = 0.25, F2 = 0.45, N = 50, and DR = 0.02.

PROBLEM 2: Change the values of F1 and F2 and run the program in Fig. 11. For example, let F1 = 0.30 and F2 = 0.35. Also, let F1 = 0.20 and F2 = 0.50.

PROBLEM 3: In Sec. III.f. a combined energy system using a diesel engine and electric generator for electric energy production and space heating is discussed. Run the program using the

parameters for the diesel engine - electric generator system as given in Sec. III.f. The ratio R2 can be taken to be 0.18 for space heating of homes and businesses.

PROBLEM 4: (This is at a higher level of difficulty than the previous problems.) Modify the program so that it computes the percentage of fuel saved by using both industrial cogeneration and a combined system for space heating of homes and businesses and electrical production. You will need to write some additional computer code. If you wish to graph the results, you must use the same value for the ratio R for both combined energy systems. Run the program for several sets of parameters.

e. Questions

QUESTION 1: Discuss your results for Problems 1, 2, and 3. Include comments on the relationship between the first and second-law efficiencies and the percentage of fuel saved.

QUESTION 2: Discuss the validity of the estimates of fuel savings due to combined energy systems from Sec. III. Base your discussion on the computer output from the Problems 1, 2, 3 and 4 (if you have done this problem.)

f. References and Footnotes.

1. The graphing algorithm is from R. Ehrlich, Physics and Computers,

Houghton-Miflin, 1973.

SEGMENT V. BIBLIOGRAPHY

a. The following references provide several tests which are indicative of the level of preparation required for using this module:

1. F. W. Sears, M. W. Zemansky, and H. D. Young, University Physics, 5th Ed., Addison-Wesley, Reading, Mass., 1976. See Chapters 15, 16, 18, and 19. The treatment uses some calculus.

2. D. Halliday and R. Resnick, Fundamentals of Physics, John Wiley, New York, 1970. See Chapters 18, 19, and 21. The treatment uses calculus.

3. S. Gartenhaus, Physics Basic Principles, Vol. I, 1st Ed., Holt, Rinehart, Winston, 1975, Ch. 15, 16, and 17. The treatment uses calculus.

4. R. H. Romer, Energy; An Introduction to Physics, W. H. Freeman, San Francisco, 1976. This text is unique in that it provides a rigorous treatment of general physics with many applications to energy production and use. There are several excellent appendices on energy. The mathematics level is college algebra throughout.

b. Varous references in this module are collected below for ease of use:

1. E. R. Berndt, "Aggregate Energy, Efficiency, and Productivity Measurement," Annual Review of Energy, Vol. 3., 1978, pp. 225-273. Presents the economic perspective toward efficiency in general and second-law efficiency in particular. The treatment of efficiency is elementary, but the economic analysis requires calculus.

2. "The National Energy Plan - Overview and Summary," Executive Office of the President, reprinted in L. C. Ruedisili and M. W. Firebaugh, Perspectives on Energy, 2nd Edition, Oxford University Press, New York, 1978, pp. 80-94. The National Energy Plan is largely outdated in specifics regarding legislative proposals. It does have some general background information on energy production and consumption which is useful.

3. J. H. Keenan, Thermodynamics, John Wiley, New York, 1948.

4. J. H. Keenan, E. P. Gyftopolous, and G. H. Hatsopolous, "The Fuel Shortage and Thermodynamics," in Proceedings of the MIT Energy Conference, MIT Press, Cambridge, Mass. 1973. This is an important paper in the development of a thermodynamics analysis of potential for reduced fuel use. The paper stresses the applicability of available work and second-law efficiency.

5. K. C. Rolle, Introduction to Thermodynamics, Charles E. Merrill, Columbus, OH. 1973. This is an elementary engineering textbook in thermodynamics. It has a good analysis of many practical power cycles. It also defines and discusses the concept of available work.

6. M. W. Zemansky, Heat and Thermodynamics, McGraw-Hill, New York, 1957. This advanced text is a classic treatment of the subject for physicists. It includes a section on unavailable work and Kelvin's Principle of Degradation of Energy. The text uses calculus freely.

7. W. Carnaham et al., "Efficient Use of Energy, a Physics Perspective," in Efficient Energy Use, American Institute of Physics, New York 1975. This long article is the definitive work on second-law efficiency and its

application to the study of efficient energy use. Although some of the treatment is elementary, it is an advanced work. However, this article should be required reading for any serious student interested in the field of efficient energy use.

8. M. H. Ross and Williams, "The Potential for Fuel Conservation", Technology Review, Vol. 79, No. 4, 1977, pp. 49-57, reprinted in L. C. Ruedisili and M. W. Firebaugh, op cit. This short article summarizes the estimates of its authors for reduced fuel use based on consideration of second-law efficiency.

9. R. H. Socolow, "The Coming Age of Conservation", Annual Review of Energy, Vol. 2, 1977, pp. 239-289. Presents an analysis of future energy demand from an international perspective. Presents the argument for recording the thermodynamic quality of energy, including the second-law efficiency.

10. L. Schipper, "Raising the Productivity of Energy Utilization", Annual Review of Energy, Vol. 1976, pp. 455-517. This article deals with some of the implications of more productive energy utilization. The conclusion is that a more productive use of energy can more economically supply much of the well-being that otherwise would be available by using more energy. The efficiency of energy use is discussed including second-law efficiency. The treatment is non-mathematical.

11. C. A. Berg, "Potential for Energy Conservation in Industry", Annual Review of Energy, Vol. 1, 1976, pp. 519-534. A general, non-mathematical treatment of the subject in the title. A short discussion of the available work in flue gases exiting from a high-temperature industrial

furnace is given in the article.

12. E. V. Somers, D. Berg, and A. P. Fickett, "Advanced Energy Conversion", Annual Review of Energy, Vol. 1, 1976, pp. 345-365. This article is a general, non-mathematical treatment of advanced energy conversion methods for electrical production. The topics include open combined-cycle and closed-cycle gas turbine power plants, magnetohydrodynamic power plants, potassium-steam binary-cycle power plants, low-temperature closed-cycle power plants, and fuel-cell power plants.
13. C. Summers, "The Conservation of Energy", Scientific American, Vol. 224, Sept., 1971, p. 148. This is an excellent popularized treatment of the general topic of energy conversion. This discussion includes useful descriptions of most of the energy conversion devices discussed in this module. Highly recommended.

c. There are some periodicals which regularly publish high quality articles on energy conversion and energy efficiency.

1. Annual Review of Energy, Edited by J. M. Hollander, for Annual Reviews Inc., Palo Alto, CA. This is an annual publication which includes a dozen or more articles by leading authorities in the general field of energy. Most of the articles are non-mathematical in approach. Each issue usually contains at least one article on energy conversion, or energy efficiency.
2. Energy Conversion, Pergamon Press, Elmsford, New York. This is a research journal which publishes highly technical articles in the area of

energy-conversion devices and systems.

d. Lastly, there are several textbooks which treat the general subject of energy in a non-mathematical manner. Their books emphasize the underlying physical principles at work in the subjects discussed.

1. J. R. Priest, Energy for a Technological Society, 2nd Ed., Addison-Weseley, Reading, Mass., 1978.
2. R. S. Rouse and R. O. Smith, Energy - Resource, Slave, Pollutant, Macmillan, New York, 1975.
3. J. M. Fowler, Energy and the Environment, McGraw-Hill, New York, 1975.
4. D. Fong, Physical Science, Energy and Our Environment, Macmillan, New York, 1976.

SEGMENT VI. AUDIOVISUAL MATERIALS

a. The amount of audiovisual materials which deal specifically with the efficiency of energy conversion is very limited. There are some films which give a general treatment of energy conversion processes, available. These are listed below.

1. "Conversion of Heat to Useful Work", 16 mm, 16 min. color. Defines heat. Discusses sources of heat and transformation of heat to useful work by various engines and, also, thermocouples. Includes nuclear, solar, chemical, electrical, and mechanical sources of heat.

   Produced by: CENO, 2600 S. Kostner Ave., Chicago, Illinois 60623

Distributed by: Indiana University
Audio-Visual Center
Bloomington, IN. 47401

2. "Energy Conversion" 58 mm, 4 min., color, Heat, Energy, and Motion Series. Main focus is on heat and its conversion to useful work. Includes chemical, electrical and heat energy. Requires no mathematics.

Produced and distributed by: BFA Educational Media
P.O. Box 1795
Santa Monica, CA. 90406.

3. "Energy and Work", 16 mm, 28 min., B.W. Discusses work as a measure of the kinetic energy transfer in various interactions. Uses a large-scale falling object demonstration, a non-linear spring, and a "Rube Goldberg" apparatus.

Produced by: Education Development Center for PSSC

Distributed by: Modern Learning Aids
P.O. Box 1712
Rochester, N.Y. 14603

4. "Conservation of Energy" (Modern Learning Aids, 27 min., b & w). Data from this film can be used to compute ideal efficiency and compare it with real efficiency.

Many more films on the general subject of energy are catologued with a brief description in:

A Cinemascope of Physics (An AAPT Film Resource Book),
American Association of Physics Teachers, 1978.

Another catalogue which is a good source of films on the general subject of energy lists all films currently available from the Department of Energy:

Energy Films Interim Catalog
Department of Energy

Available from:

DOE, Film Librarian
P.O. Box 62
Oak Ridge, TN. 37830

b. The following audio tape cassette is available. It gives a discussion of the laws of thermodynamics with applications to various fields. One of the applications is to energy conversion in heat engines.

"Laws of Thermodynamics" and "Applications of the Laws of Thermodynamics", Audio Learning Discussion Tape, Audio Learning Limited, 84 Queenway London W2